SATELLITE RECEPTION OF REENTRY VEHICLE TELEMETRY

THESIS

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

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Preface

The reader is cautioned against taking any calculated result in this thesis out of context. Every conclusion is based on a series of assumptions, any one of which could significantly alter the conclusion if changed. The assumptions behind each result are given throughout the thesis, and in the concluding chapter there is a brief summary of the conditions under which conclusions are valid. It is an honest attempt to point out the limitations of the analysis. However wise or unwise this self examination is for a student attempting to obtain a good grade, I feel that it is the least I can do for the reader and for my generous sponsor.

This thesis was sponsored by the Office of Plans and Programs, Eastern Space and Missile Center, Patrick AFB, Florida. I wish to thank Mr. Edward Herrburger and Mr. Robert Wilfong of the ESMC for their enthusiastic support and encouragement during this effort. I hope the result is of some assistance in their work.

I would also like to thank Dr. Vaqar Syed for prudently urging me to begin writing this thesis early, and Dr. Thomas Jones for his very helpful information on reentry vehicle characteristics.

Richard W. White Jr.

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Abstract

This thesis is intended to be a tool for planners of a reentry vehicle to satellite telemetry link. However, it may be a useful resource to anyone interested in satellite communications, especially those who wish to examine the S-band capability of the Tracking and Data Relay Satellite (TDRS). The thesis should be a stand alone reference for a general overview of the problems concerned. Most of the major problems involved in establishing a telemetry link have been set forth in this one source. The reader is briefed on each problem in sufficient detail to gain some insight as to how the problems affect the quality of the link, how the problems are related to each other, and some of the tradeoffs that can be performed. A broad range of antenna and transmitter combinations are examined, and their performances are compared.

Specifically, this thesis examines free space loss, rain loss, gain and 3 dB beamwidth of parabolic, slot, and dipole antennas, parabolic antenna footprint on the Earth, the concept of received signal strength, reentry vehicle and satellite characteristics, increasing transmit power, varying frequency from 1 to 10 GHz, increasing antenna effeciency, and increasing receiver sensitivity.

Some preliminary conclusions are drawn, and areas for further study are recommended.

SATELLITE RECEPTION OF REENTRY VEHICLE TELEMETRY

I. Introduction

Background

When a missile is launched from Cape Canaveral or at sea, its performance is evaluated in part by telemetry transmitted back to Earth by the missile. Currently, a lot of money, time, and effort are spent on equipment necessary to receive the telemetry. Because the telemetry is transmitted on a line-of-sight radio beam, tracking stations have been established on islands and ships scattered across the Atlantic Ocean. Each station can monitor the signal for only a few minutes, as the missile passes from horizon to horizon during that time. Thus, even with several widely geographically separated tracking stations in use, there are periods of time when the missile is out of receiving range, and the telemetry data is lost.

A proposed solution to this problem is to send the telemetry not to the ground, but to a tracking satellite in a geostationary orbit. The satellite would be able to continuously monitor the missile's telemetry across the entire Atlantic Ocean, and relay the signal back to a single tracking station on Earth. This solution has the advantage of providing a significant increase in the amount of data received for many different launch and impact points. It may also eliminate the need for maintaining most of the ground stations.

The Problem

This thesis examines the feasibility of using a satellite to receive telemetry signals from a reentry vehicle (RV). A reentry vehicle is an object carried inside the nose cone of a missile. Typically several reentry vehicles, each transmitting its own telemetry signals, are ejected from a missile during its flight. Specifically, this thesis examines what is necessary to send a signal from a reentry vehicle to a satellite in geostationary orbit.

Scope

Given the constraints of a reentry vehicle (such as transmitter size and power, antenna configuration, required data rate, and allowable bit error rate) and reasonable constraints on the satellite, the following three questions are addressed:

1. What levels of transmit power are feasible for the reentry vehicle?
2. What possible antenna size and configurations are feasible for:
    a. the satellite?
    b. the reentry vehicle?
3. What is the required sensitivity of the receiver aboard the satellite?

To keep the problem within the time constraint of a thesis project, the cost effectiveness of the proposed satellite relay system was not examined. However, a ground rule for this project was that the amount of engineering changes (and increased cost) to the reentry vehicle should be kept to a minimum. A satellite orbit lower than geosynchronous was not considered, as this would have resulted in an additional reentry vehicle launch window constraint and other problems. The return link from the satellite to the ground station and the sending of signals from the ground are not discussed. Although it is desirable for the satellite to receive telemetry from many reentry vehicles simultaneously, only one telemetry link is considered in this thesis.

This thesis is intended to be a tool for planners of a reentry vehicle to satellite telemetry link. It should be a stand alone reference for a general overview of the problems concerned. Most of the major problems involved in establishing a link have been set forth in this one source. The reader is briefed on each problem in sufficient detail to gain some insight as to how the problems affect the quality of the link, how the problems are related to each other, and some of the tradeoffs that can be performed. A broad range of antenna and transmitter combinations are examined and their performances are compared. The reader can then use the information presented to determine which combination(s) are worthy of further investigation.

Assumptions and Current Knowledge

The crux of the problem is that the reentry vehicle is assumed to be heavily constrained in possible transmitter and antenna configurations. The antenna must provide high gain, yet still remain small, be lightweight, and be able to withstand the severe vibration and thermal effects associated with reentering the Earth's atmosphere. Space, electrical power, and allowable weight for the transmitter are limited. Recently the National Aeronautics and Space Administration launched a Tracking and Data Relay Satellite (TDRS). The TDRS performs a function similar to that of the proposed telemetry relay satellite, relaying communications between the Space Shuttle and the Earth. The difference between the Space Shuttle and a reentry vehicle, however, is that the space, power, and weight constraints are considerably relaxed aboard the Space Shuttle. For example, the Space Shuttle is large enough to have a 3 foot dish tracking antenna mounted in its cargo bay (2:1,500).

Standards and Approach to the Problem

The first task of the thesis project was to research the constraints of a typical reentry vehicle. The size and weight of the antenna and telemetry transmitter used in this thesis were based on the approximate size of reentry vehicles in use today. The required data rate, transmitting frequency, and allowable error rate for the telemetry used in this thesis were also typical of reentry vehicles in use today. A search was made of published literature so that work performed on problems similar to the thesis problem could be compared. The author gained much benefit from researching the TDRS communication system, especially with regard to the mathematical relationships used in link performance calculations. For example, there are mathematical equations which describe how a signal deteriorates as it propagates through space, and how signal strength is related to data rates. The equations were used to calculate a range of possible received signal strengths. This, in turn, determined what type of antenna configurations and transmitter performance specifications were feasible. The number of feasible configurations was severely limited by reentry vehicle constraints. The constraints reduced the number of calculations to be performed, as only a few configurations needed to be examined.

To arrange the data in a meaningful form, a series of graphs depicting reentry vehicle parameters versus satellite parameters were generated. For example, a graph of reeentry vehicle transmit power versus satellite antenna size is included.

The proposed system was considered feasible if all the reentry vehicle constraints were met, and if hardware exists (or will soon exist) that is capable of the performance specified in the graphs. The latter required a brief survey of available and planned space qualified equipment for transmitting and receiving telemetry. Again, information from the TDRS program provided the most useful information regarding the performance of state of the art hardware. Calculations were made over a limited range of parameters as there was no point in calculating the performance of a 50 watt transmitter, especially when most telemetry transmitters of this type are capable of producing only 5 watts output.

Two Approaches Taken

It is theoretically possible to construct a satellite of sufficient sensitivity that no modifications to existing reentry vehicles would have to be made. Similarly, it is possible (but not reasonable) to extensively modify the reentry vehicle such that its transmit power is so great that the TDRS currently in orbit would be able to receive a high data rate telemetry signal. Thus two approaches are taken in this thesis. In the first approach, the level of sophistication for the satellite is very high and the modifications to existing reentry vehicle is minimal. In the second approach, the reentry vehicle sophistication is increased significantly, reducing the required size of the antenna aboard the receiving satellite. The former approach is preferred over the latter, since modifying one satellite is apparently easier than modifying thousands of reentry vehicles. However, by comparing the two approaches, the reader should gain a better understanding of the problems and tradeoffs involved in making the system work. In many instances the best approach is not always the easiest, and a comparison of different approaches is useful in planning for the uncertain future.

II. Mathematical Relationships

Purpose

This chapter familiarizes the reader with the equations necessary to describe the performance of the communications link between the reentry vehicle and the satellite. Some of the equations are approximations, but they are accurate enough for comparison purposes. More accurate expressions would not add to the accuracy of the solutions, as they would require knowledge of minute details of the system (such as the surface roughness of the antenna) which are yet to be defined.

Free Space Loss

The degradation in signal strength due to its propagation through free space is given by (5:84):

$$FSL = 20 \text{ Log} \left(\frac{\lambda}{4\pi z} \right) \tag{1}$$

where

FSL = Free Space Loss in dB (usually a negative quantity)

λ = wavelength of signal

z = distance traveled

Assuming worst case conditions (reentry vehicle at sea level and satellite at geosynchronous altitude), z = 35,784 km. At this altitude, the Free Space Loss ranges from -183.5 to -203.5 dB for frequencies between 1 and 10 GHz (See Figure 1). It should be noted that a 6 dB improvement would be obtained if the satellite to reentry vehicle distance was cut in half (z = 17,892 km). Although reentry vehicles may reach altitudes of 600 km or more, worst case distance is consistantly used throughout the thesis.

Rain Loss

For frequencies under 10 GHz, the degradation of the reentry vehicle's telemetry signal due to rainfall is on the order of -0.1 dB and can be ignored (13:574).

Antenna Gain

The gain of a parabolic dish antenna is given approximately by (16:66):

$$g = 10 \, \text{Log}\left[\left(\frac{\pi d}{\lambda}\right)^2 n\right] \tag{2}$$

where

g = gain (in dB)

λ = wavelength of signal

d = diameter of dish

n = antenna efficiency factor

Typically, the antenna efficiency factor for space application antennas is 0.4 (see Appendix B for justification).

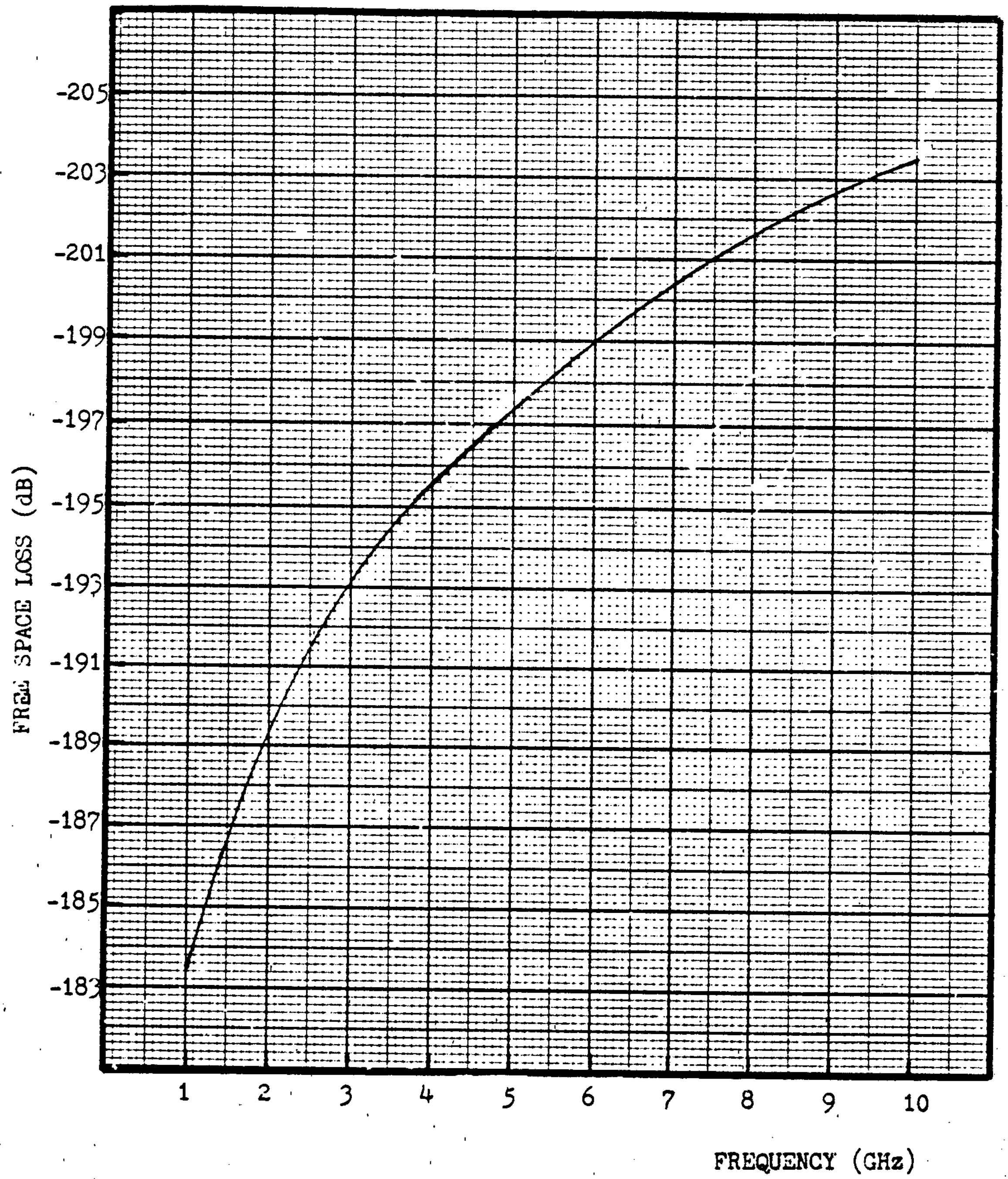


Figure 1. Space Loss Versus Frequency For Geosynchronous Orbit

The one half power beamwidth of a parabolic dish antenna is given approximately by (21:274):

$$3dB \quad BW = 70\lambda/d \qquad (3)$$

where

3 dB BW = one half power beamwidth (in degrees)

λ = wavelength of signal

d = diameter of dish

Another type of antenna used in this thesis is the long dipole. Typically the gain of this antenna is 2.148 dB, and the one half power beamwidth is 78 degrees. The length of the antenna is one half the wavelength of the transmitted signal, and its gain is independent of frequency (18:597,5:89).

Footprint

If the area of satellite antenna coverage is drawn on a map of the Earth, the enclosed area is referred to as the footprint of the antenna. In general, the higher the gain of the antenna the narrower the beamwidth and the smaller the footprint. While it is desirable to increase the gain of an antenna, de reasing the footprint is undesirable. Reentry vehicles typically travel thousands of kilometers over the surface of the Earth. If the footprint is smaller than the travel path of the reentry vehicle, the satellite antenna will have to track the reentry vehicle. This significantly adds to the complexity of the satellite, as a steering motor for the antenna, as well as a guidance mechanism for accurate pointing, will be required. Currently the TDRS is able to point its 4.9 m diameter dish antenna at an orbiting Space Shuttle with sufficient accuracy to achieve a high data rate. The TDRS is in geosynchronous orbit, and the Space Shuttle's orbit is similar to the path of the reentry vehicle. Therefore, at first glance, tracking appears to be a solved problem. However, the antenna for the proposed telemetry relay satellite will be much larger than the one used on TDRS. This means that its footprint will be smaller and the required pointing accuracy will be greater. In addition, the more mass the antenna has, the more difficult it is for the pointing motor to move the antenna with the same accuracy. However, the large distance of 35,784 km between the reentry vehicle and the satellite reduces the amount of change in pointing angle the antenna must undergo, and reduces the rate at which the pointing change takes place. The fact that the reentry vehicle moves in a straight line is yet another factor which reduces the difficulty in pointing the satellite antenna at the reentry vehicle.

If a reentry vehicle travels a distance of 8,000 km across the surface of the Earth, the satellite antenna must move a total of approximately 12.756 degrees to track the RV throughout its flight (see Equation (4) below). If the RV takes 40 minutes to cover the 8,000 km distance, antenna pointing must be changed at a rate of 0.3189 degrees per minute, or 0.0053 degrees per second.

The approximate size of an antenna footprint can be found through simple geometry. If the surface of the Earth is assumed to be flat, and if ϕ is the 3 dB beamwidth as shown in Figure 2, then the satellite antenna footprint is given by:

$$\text{Footprint Diameter (in km)} = (2\,[\tan\,(1/2\,\phi)]\;35{,}784) \qquad (4)$$

This equation is derived from the fact that triangle abc in Figure 2 is a right triangle, and that tan $(1/2\,\phi)$ is equal to length bc divided by 35,784 km. The footprint diameter given by Equation (4) is a minimum value. It is accurate for antennas with small beamwidths aimed close to the equator. For a parabolic dish antenna, the footprint is circular when pointed at the equator. As the antenna is pointed closer to the polar regions, the footprint elongates due to the curvature of the Earth.

Received Power

The signal strength of the reentry vehicle telemetry signal at the receiving satellite antenna is given by (7:A-3):

$$\text{Received Signal Strength (in dBw)} = 10\ \text{Log}\ \frac{P}{1\ \text{watt}} + L + G \quad (5)$$

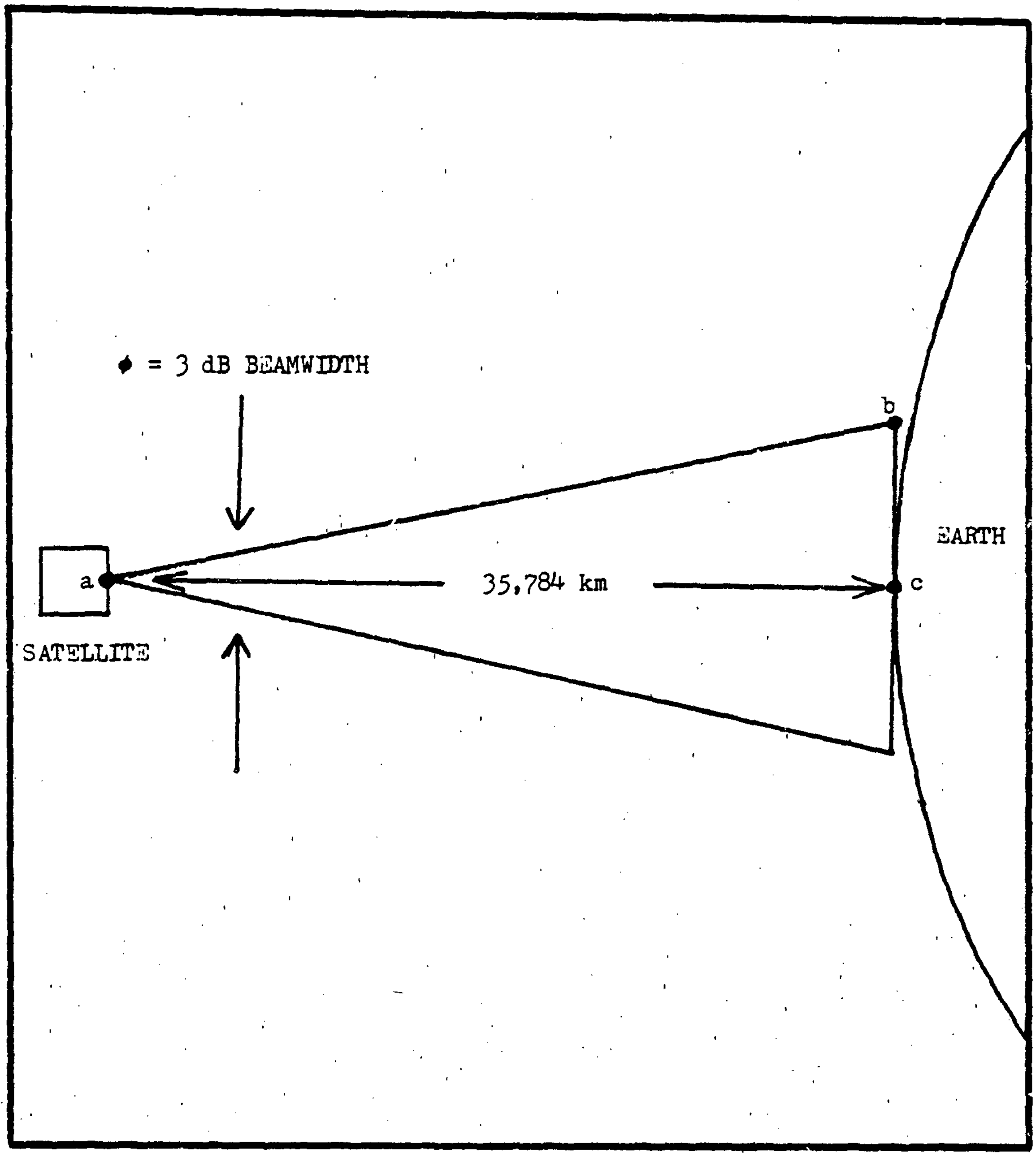


Figure 2. Satellite Antenna Footprint

where

P = Reentry vehicle transmit power in watts.

L = Free Space Loss (Equation (1)) and other losses in dB.

G = Gain of reentry vehicle antenna in dB.

The above equation is derived from the definition of dBw and the fact that it is acceptable to add units of dB and dBw (see Appendix C for justification).

The dominant loss factor in Equation (5) is free space loss. Other losses which occur include rain loss, antenna pointing loss, signal polarization loss, and coupling losses between the reentry vehicle transmitter and antenna (7:A-2,A-3). These losses are very small compared to free space loss, and many of them (such as coupling loss) depend on the specific reentry vehicle design. Thus it is more convenient, as well as practical, to group these losses separate from free space loss and consider them later. In the preliminary planning stage of a space link system, it may be most useful to calculate the required signal strength, and then add a few dB of antenna gain or increase transmit power, to account for the as yet undefined losses in the system. The practice of increasing the system's performance so that the link is maintained under less than ideal conditions (such as less than expected antenna gain) is referred to as establishing a link margin. For the TDRS system the link margin is roughly 7.7 dB (7:A-8).

Required Power Concept

The amount of power required at the satellite receiving antenna directly depends on the desired data rate. It will be shown later that even without any modifications to the antennas of currently used reentry vehicles or the Tracking and Data Relay Satellite, it is possible to establish a communications link with a 1×10^{-5} bit error rate. However, the data rate of such a link would be unacceptably low.

To compute the required power for the system, it is necessary to use Equations (1), (2), and (5). (Equations (3) and (4) relate to the separate problem of tracking and pointing accuracy). Since the exact required data rates for future systems are unknown, many different values are placed into these equations later in this thesis, and various combinations of variables are graphed. The relationship between data rate and received power is then derived using the sensitivity of the TDRS receiver as a base line.

III. The Hardware

The Reentry Vehicles (RV)

Most reentry vehicles are cone shaped, with a typical height of only 100 cm and a base diameter of 40 cm. Electric power is commonly provided by a 28 volt battery. There is not much space inside a reentry vehicle for a telemetry system. The bulk of the RV is made up of the radar, guidance and control, and warhead sections.

A rough mission profile for a reentry vehicle would be: separation from the missile shortly after launch, attain a maximum altitude of approximately 637 km (17:24) attain a speed of 3,000 meters per second (17:255), reach a spin stabilization rate of 10 radians per second (95.5 rpm) (17:255), and travel thousands of kilometers before impact (17:294). It is desirable for reception of reentry vehicle telemetry to be continuous from separation to impact (including reentry if possible).

The reentry vehicle antenna system usually consists of three cavity backed slot antennas (see Figure 3) equispaced around the cone. The transmitter power, usually 5 watts, is equally divided among the antennas. It is common for reentry vehicles to have several different telemetry transmitters and multiple sets of antennas. In addition, some RVs have a single antenna protruding from their base. Currently S-band

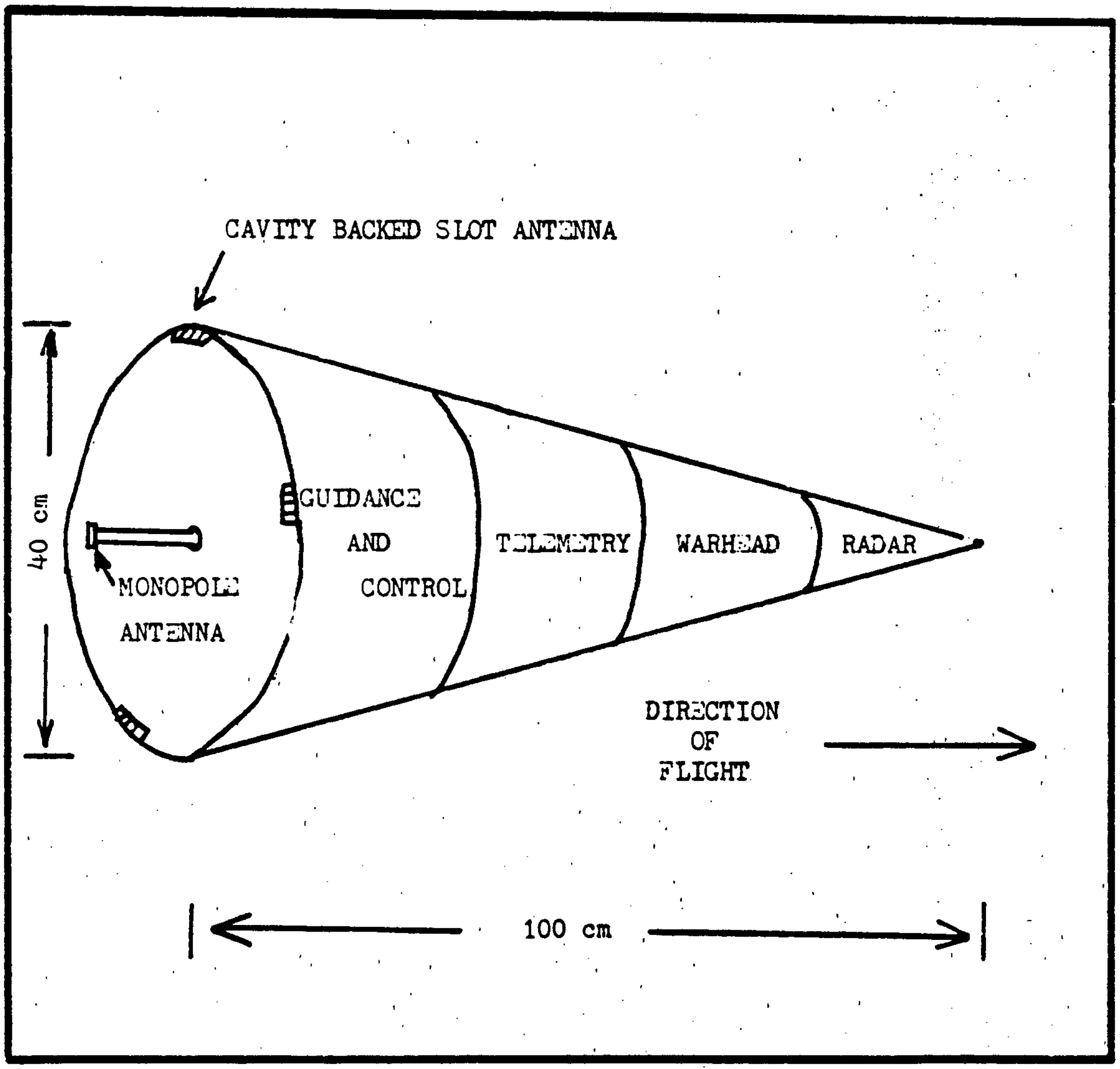


Figure 3. Typical Reentry Vehicle

frequencies near 2260 MHz are used for data transmission. Each data link may have bit rates of approximately 250 to 750 Kbps. Thus, for RVs with multiple transmitters, the total data rate could easily reach 1 Mbps. The standard maximum allowable bit error rate (BER) is 1×10^{-5}.

It is not necessary to go into greater detail about the current design of reentry vehicles. The specific design and performance parameters differ from one RV to the next, and they are constantly changing as technology and mission requirements change. However, there are several aspects about reentry vehicles that are likely to remain the same, and they will influence the telemetry link design. They are:

1. High forward velocity
2. High rotation rate
3. Limited physical space
4. Limited electrical power
5. Must endure reentry of Earth's atmosphere
6. Total of 1 Mbps telemetry
7. Maximum bit error rate of 1×10^{-5}

Note that one possible design option for relaying the reentry vehicle telemetry to a satellite is to use a single, high gain, RV antenna. Combining all the telemetry into one link would mean that the data rate of that link could be 1 Mbps or higher. This would involve a more sophisticated, and probably higher power transmitter (since battery power would be dedicated to one rather than several transmitters).

A less radical engineering change would be to retain separate transmitters, (multiple transmitters do not necessarily provide less efficient conversion of the limited input battery power) but improve the antenna system.

The Satellite

The constraints on the proposed telemetry relay satellite are far fewer than those for the reentry vehicle. The primary consideration is the additional weight of a large antenna. Currently the heaviest payload capable of being placed into geosynchronous orbit by existing rocket boosters (such as the Inertial Upper Stage, or IUS) is between 5,000 and 6,000 pounds (20:157), although this amount is certain to increase over the next decade, with the introduction of the Centaur G-prime booster. The Tracking and Data Relay Satellite is one of the heaviest communications payloads placed in orbit to date, weighing approximately 4,700 lbs (20:154). The TDRS also has one of the largest receiving antennas (4.9 m) ever deployed in space. (The ATS-6 satellite launched in 1974 had a 9.1 meter antenna, but it was used solely for broadcasting (6:93)). It will be shown later that 4.9 m is far too small an antenna for the required reentry vehicle data rates. Thus an increase in spacecraft weight due to a larger antenna appears inevitable.

Recently Lockheed Missiles and Space Company tested a section of a 55 m parabolic antenna (12:70). If current schedules hold, a test of this antenna will take place in space in 1988. The antenna consists of 40-80 ribs (depending on performance requirements), with a knit wire mesh attached to them. Each of the ribs weighs 20 lbs. Assuming worst case conditions (80 ribs) the antenna would weigh 1,600 lbs, not counting the wire mesh and the central body to which the ribs are mounted. Thus the spacecraft weight could increase by as much as 2,000 lbs over the TDRS weight if this antenna is used. The weight of the antenna is critical, as adding 2,000 lbs to the 4,700 lb TDRS would mean that the booster rockets currently used in launches aboard the Space Shuttle (such as the IUS) might not be able to lift the satellite into geosynchonous orbit. While a more powerful booster may be available by the time such a satellite is developed, it is still desirable to plan conservatively and select the smallest satellite antenna possible. Another restriction worth noting is that the satellite and booster must be able to fit into the 15 by 60 foot cargo bay of the space shuttle (9:7.2) (the IUS is 16.4 ft long (20:157)). The performance of the 55 meter antenna is examined in the following chapter and is compared to the performance of antennas of other sizes.

The Tracking and Data Relay Satellite is capable of receiving S-band telemetry at a data rate of 1.024 Mbps with a bit error rate of 1 x 10-5 when the received power at the satellite antenna is only -165 dBw (7:4-84). As shown in Figure 4, the log of the data rate is linearly related to the

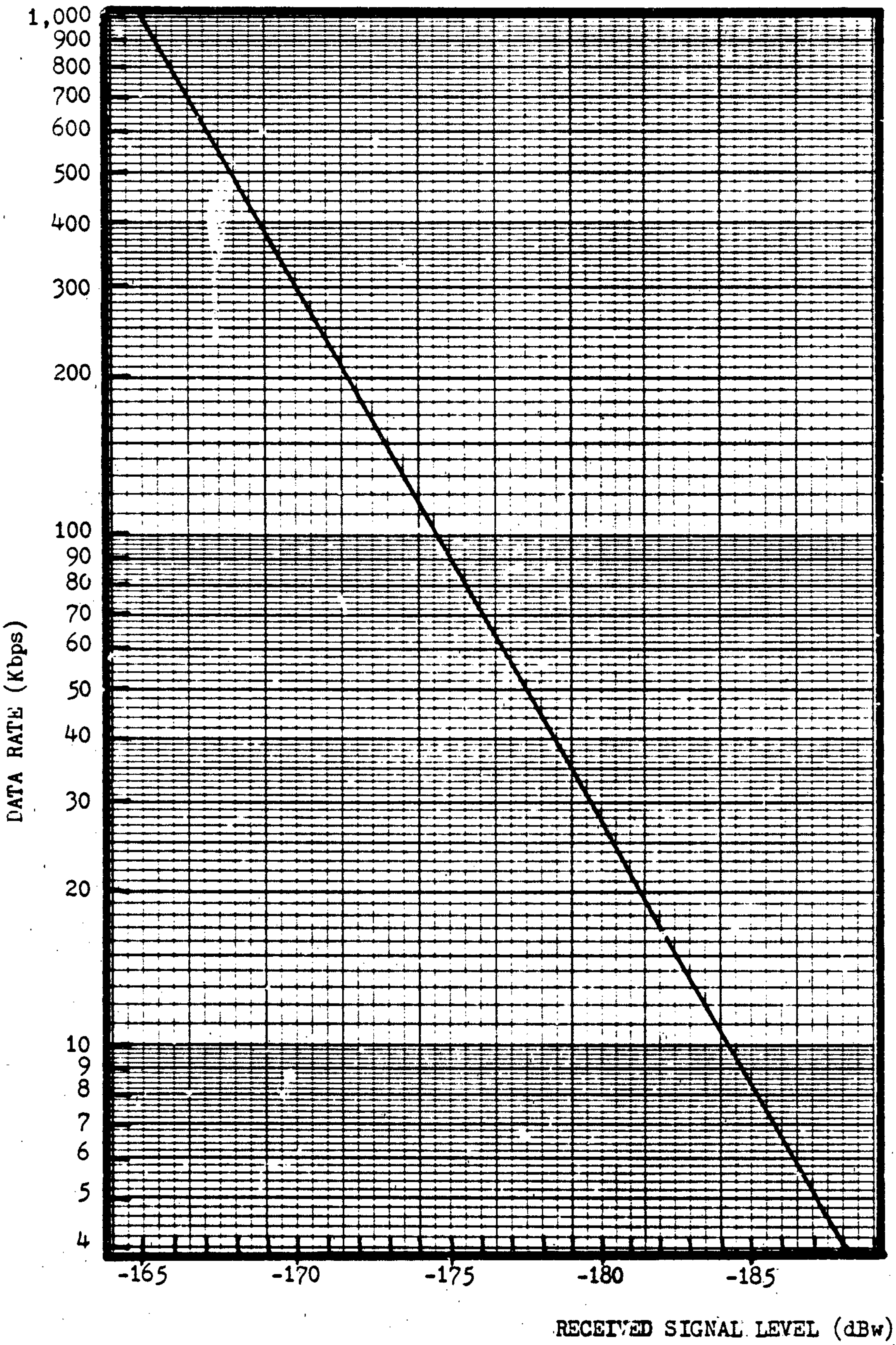


Figure 4. TDRS S-band Performance

received signal level. From the graph it is easy to determine what is the minimum received power in order to achieve a certain data rate (2.8 dBw has been added to the required signal level numbers as link margin for polarization loss). Since there is a linear relationship in Figure 4, it can be shown that for the TDRS S-band single access channel (see Appendix A for derivation):

$$\text{Log (bit rate)} = 0.1047 \times (\text{received dBw}) + 23.2868 \quad (6)$$

Similar figures and a modified Equation (6) will be used in the following chapter to evaluate the performance of different size antennas.

IV. The Sophisticated Satellite Approach

The Satellite

Table 1 shows various characteristics of parabolic dish antennas as they increase in size. The antenna diameters range from approximately TDRS S-band antenna size to 85 meters (278.87 ft). All calculations were performed based on antenna efficiency of 40 percent and a transmit frequency of 2260 MHz.

Table 1

Parabolic Antenna Characteristics

Diameter (m)	Gain(dB) Eq (2)	Beamwidth Eq (3)	Footprint(km) Eq (4)	Refer to Figure " "
5	37.5	1.858	1160.5	5
10	43.5	0.929	580.2	6
15	47.0	0.619	386.6	7
20	49.5	0.465	290.4	8
25	51.5	0.372	232.3	9
30	53.0	0.310	193.6	10
35	54.4	0.265	165.5	11
40	55.5	0.232	144.9	12
45	56.6	0.206	128.7	13
50	57.5	0.186	116.2	14
55	58.3	0.169	105.5	15
60	59.1	0.155	96.8	16
65	59.8	0.143	89.3	17
70	60.4	0.133	83.1	18
75	61.0	0.124	77.4	19
80	61.6	0.116	72.4	20
85	62.1	0.109	68.1	21

This frequency was chosen because it is a common S-band telemetry frequency, and because it is the approximate frequency used for the TDRS performance graph in Figure 4.

The TDRS performance is the basis for calculating the performance of the antennas listed in Table 1. The TDRS receiver was selected for use in this thesis as it was designed specifically for receiving telemetry from a low power source, and because it is representative of the state of the art hardware that is currently operating in space. Thus the same frequency used for the TDRS must be used for calculating antenna gain, beamwidth, footprint, and performance since all of these variables depend on the wavelength of the transmitted signal.

The performance of the antennas listed in Table 1 are given in Figures 5 thru 21. The performances were determined by removing the gain of the TDRS S-band receive antenna, 37.3 dB (15:422) (see also Appendix B on antenna efficiency), and then replacing it with the gain of the antennas from Table 1. For example, a bit rate of 1.024 Mbps requires a minimum received signal level of -165 dBw for TDRS. Without the TDRS antenna, the required signal level would be: -165 dBw + 37.3 dB = -127.7 dBw. If a 30 meter antenna is used, then the required signal level for a 1.024 Mbps data rate would be only -127.7 dBw -53dB = -180.7 dBw. As expected, the larger antenna allows the same data rate given a weaker signal. In fact the 15.7 dB increase in antenna gain has enabled the same data rate to be achieved with a 15.7 dBw weaker signal.

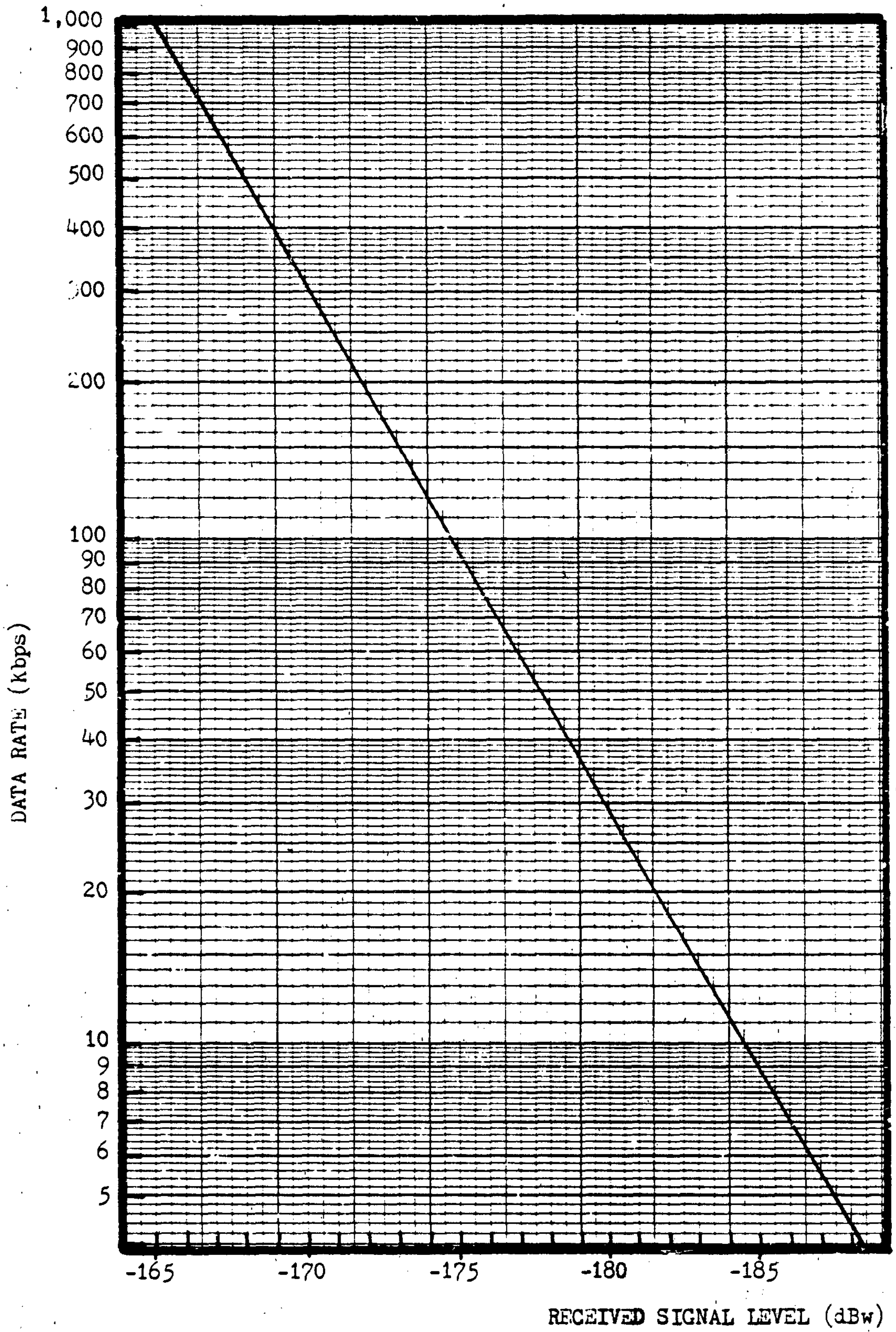


Figure 5. 5 Meter Antenna Performance

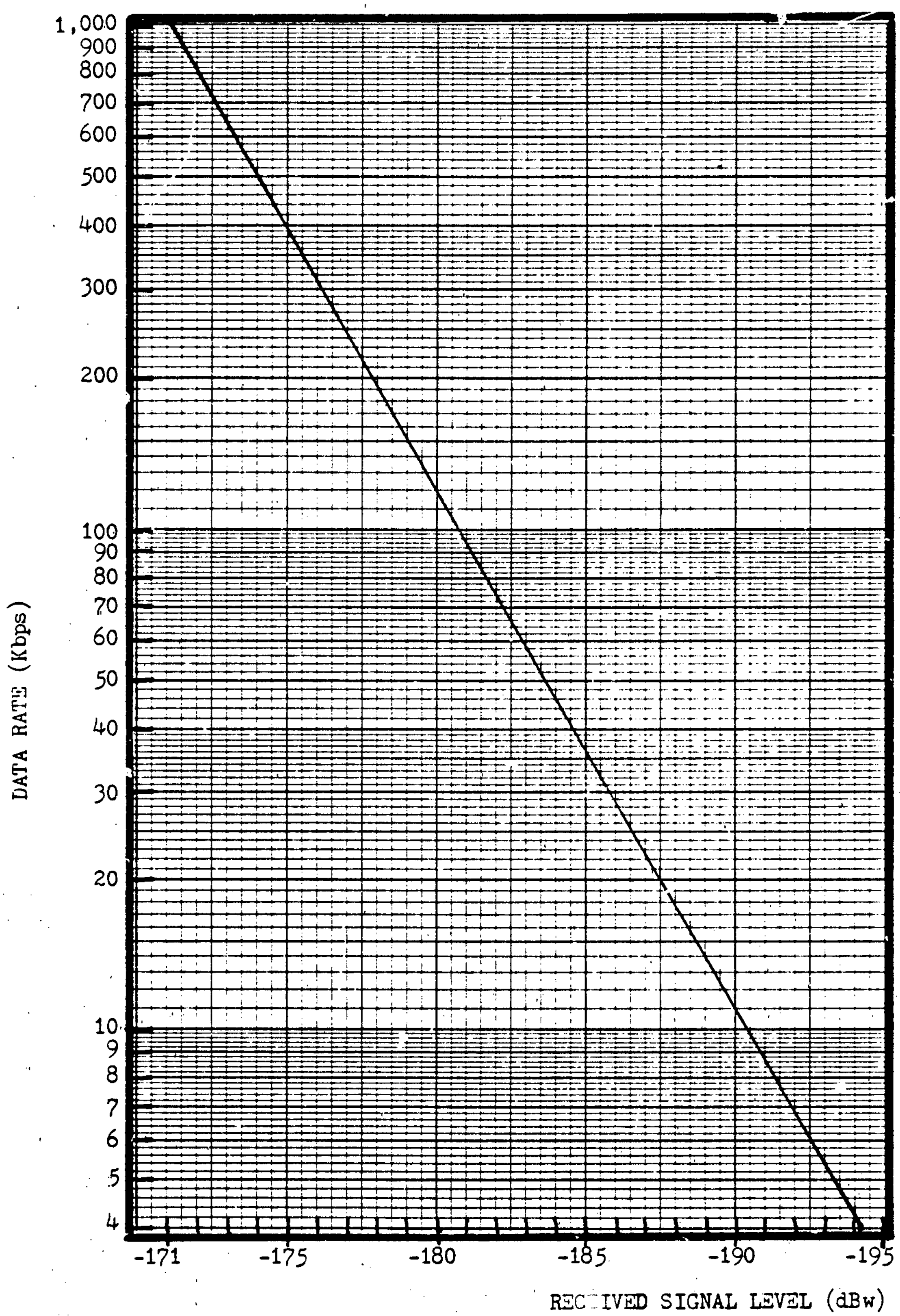


Figure 6. 10 Meter Antenna Performance

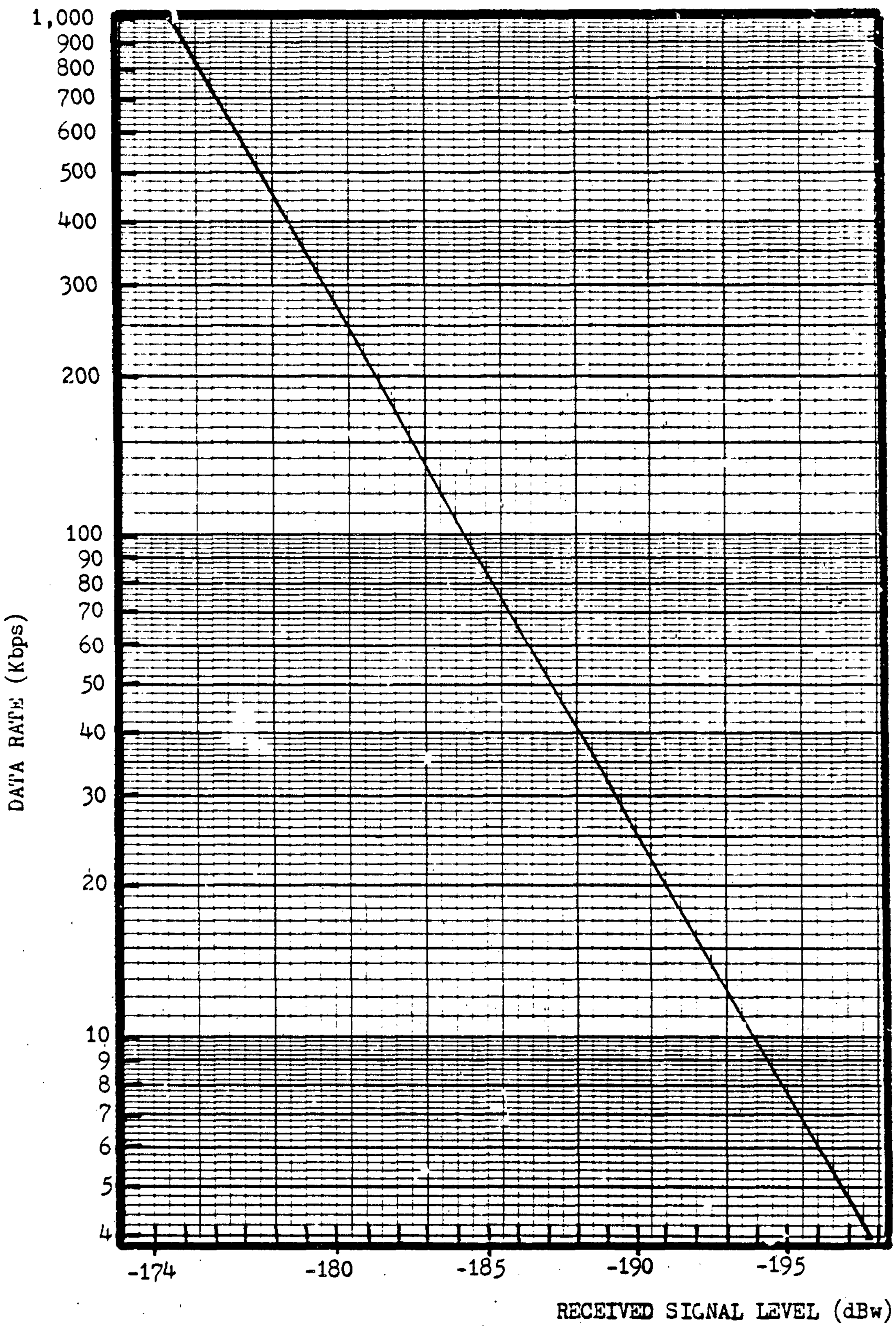


Figure 7. 15 Meter Antenna Performance

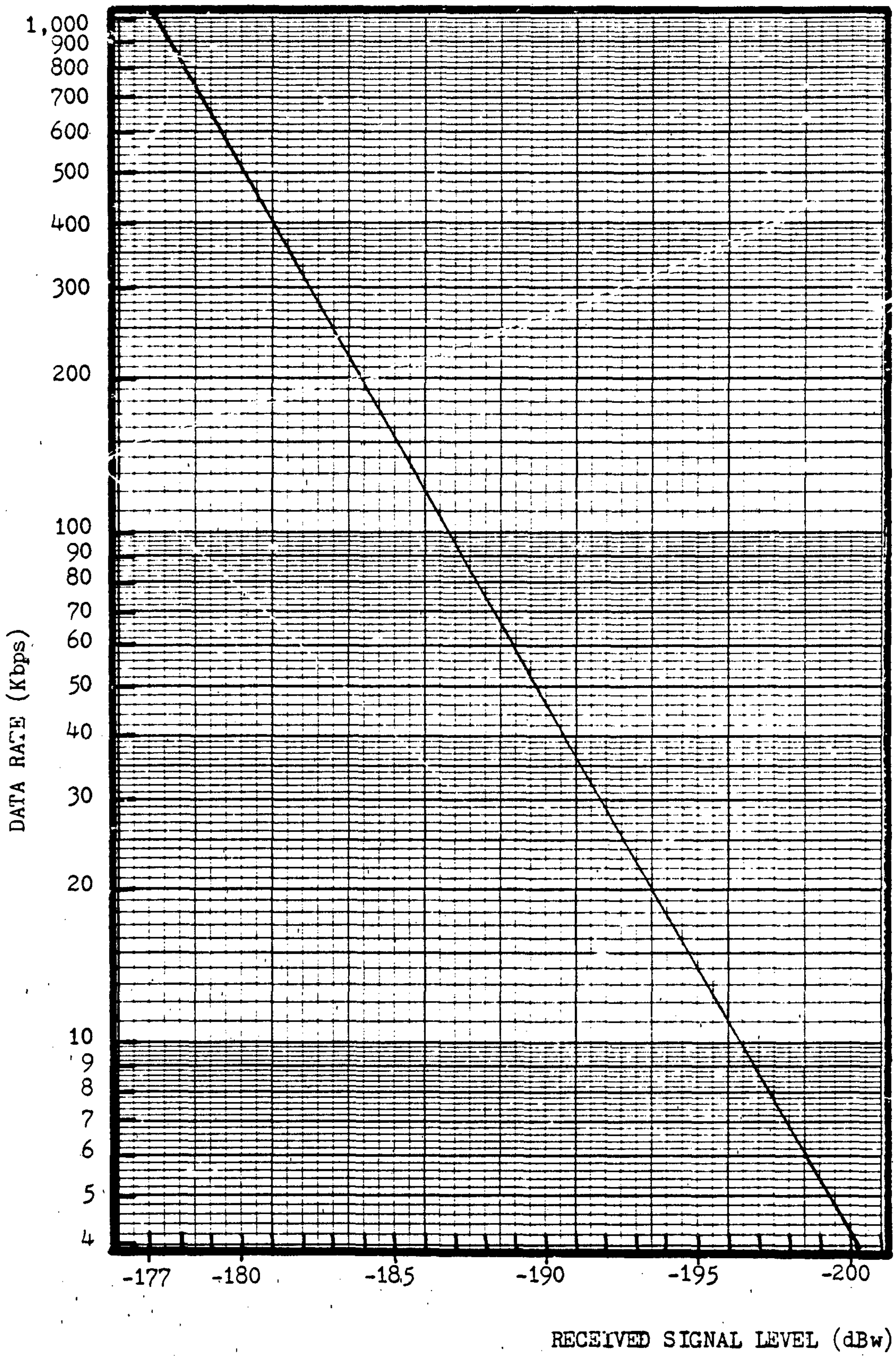


Figure 8. 20 Meter Antenna Performance

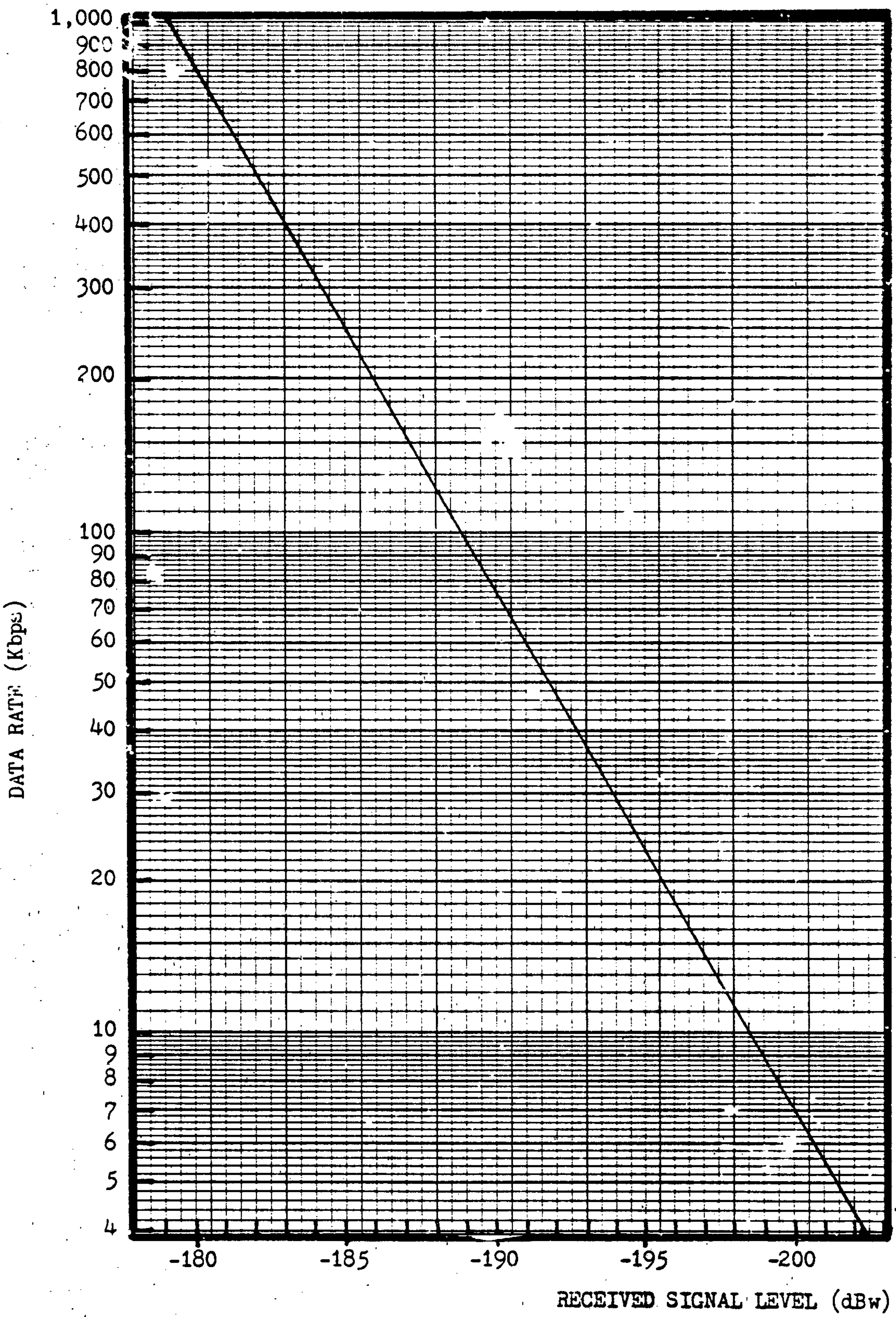


Figure 9. 25 Meter Antenna Performance

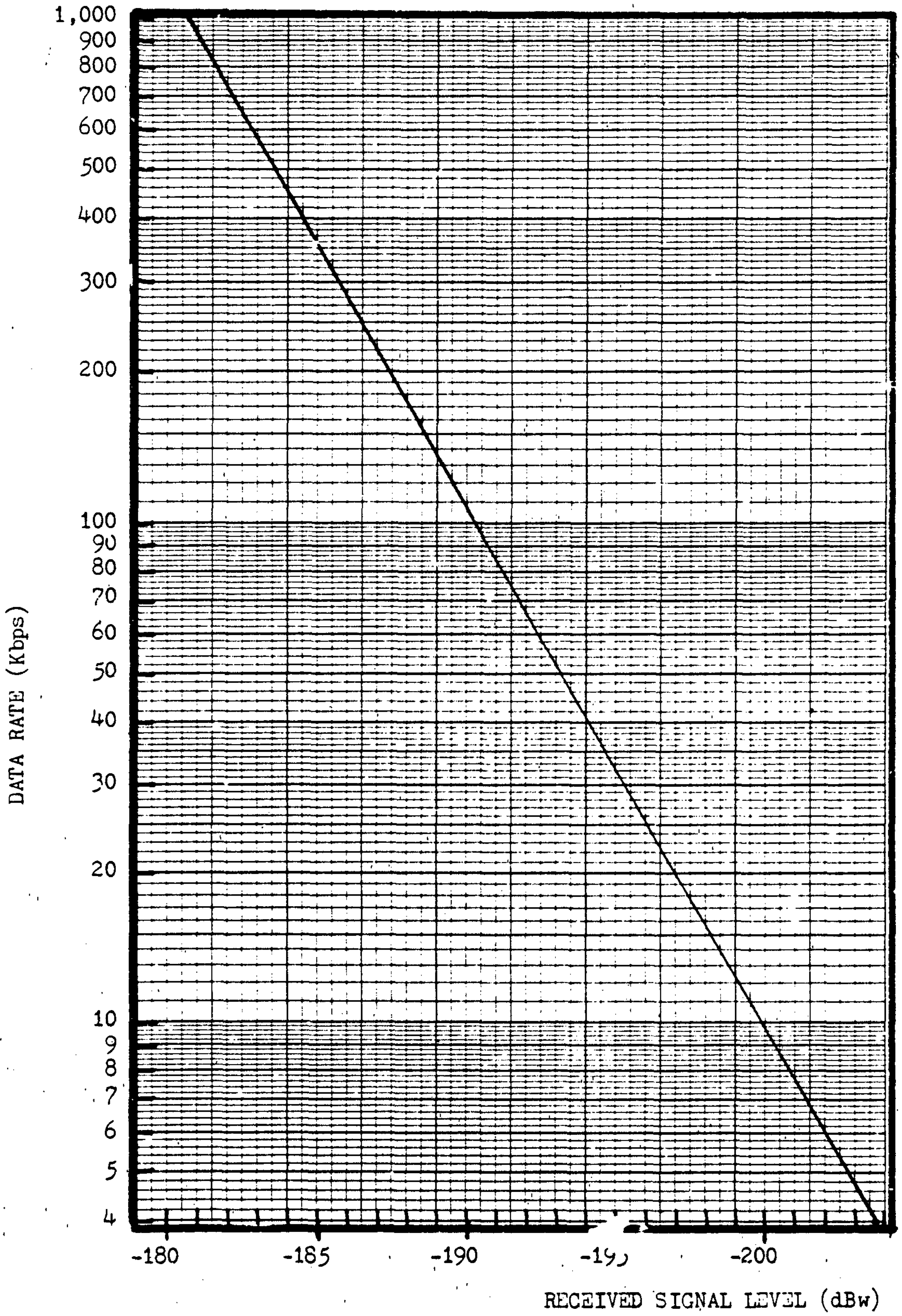


Figure 10. 30 Meter Antenna Performance

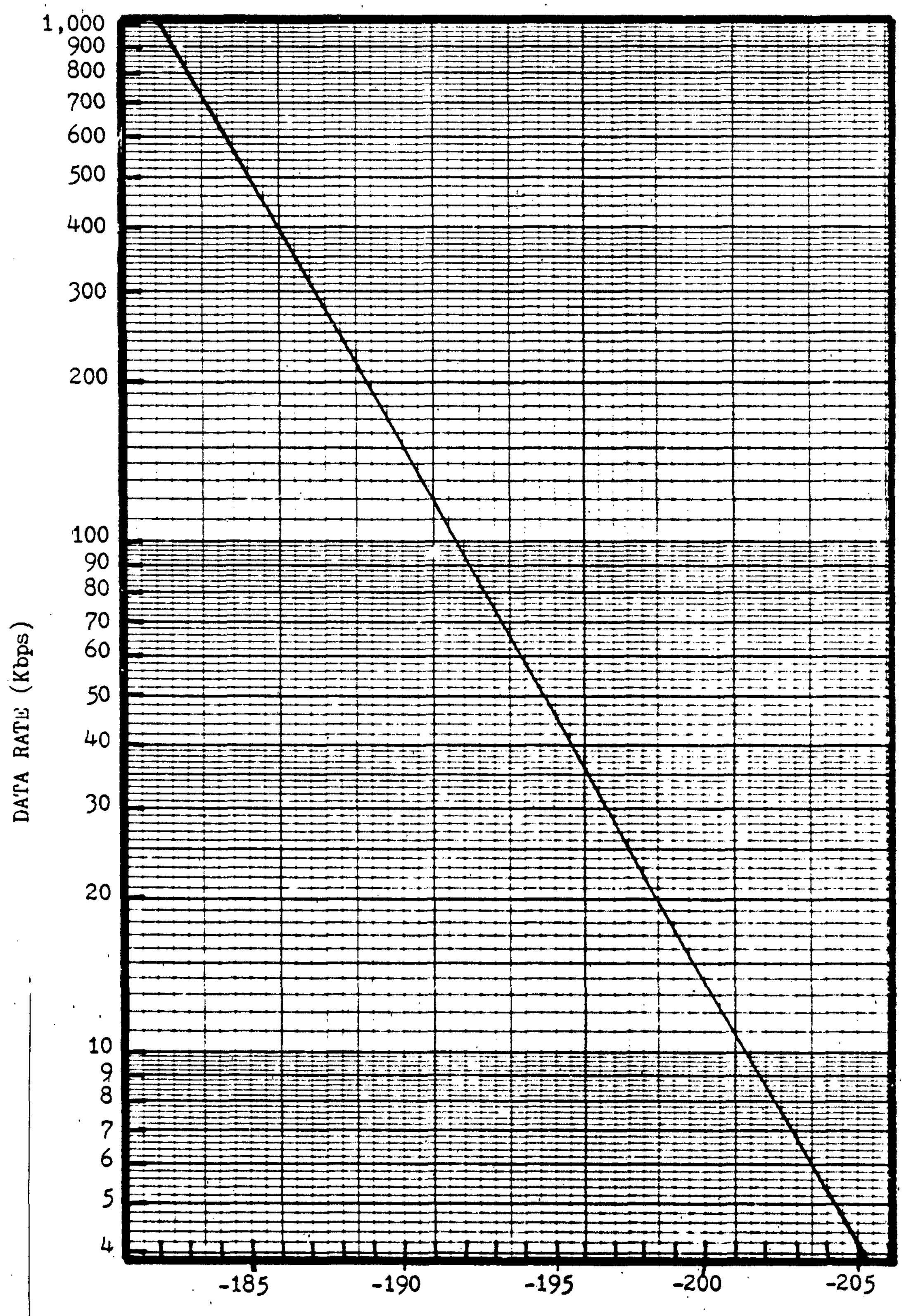


Figure 11. 35 Meter Antenna Performance

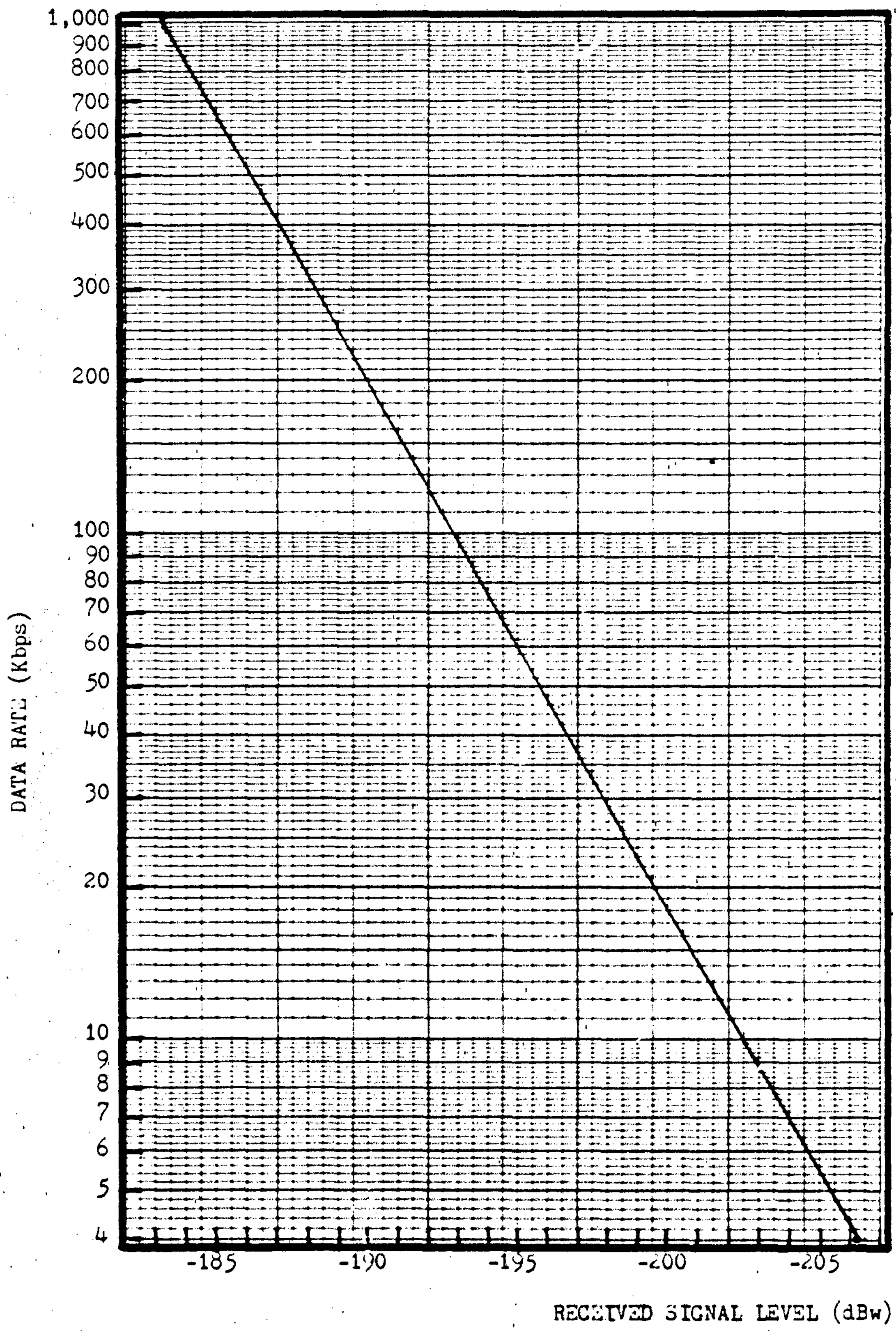


Figure 12. 40 Meter Antenna Performance

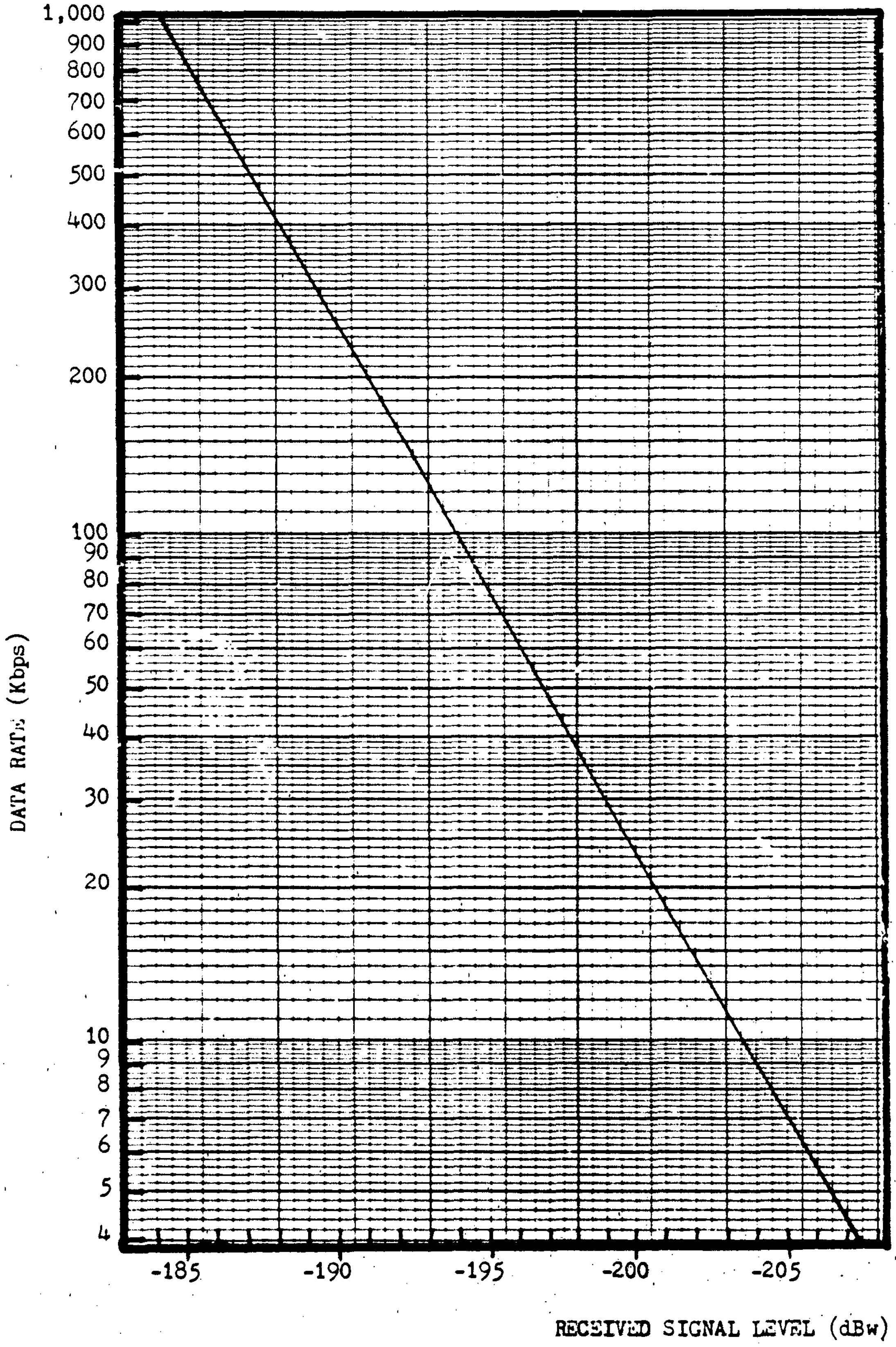


Figure 13. 45 Meter Antenna Performance

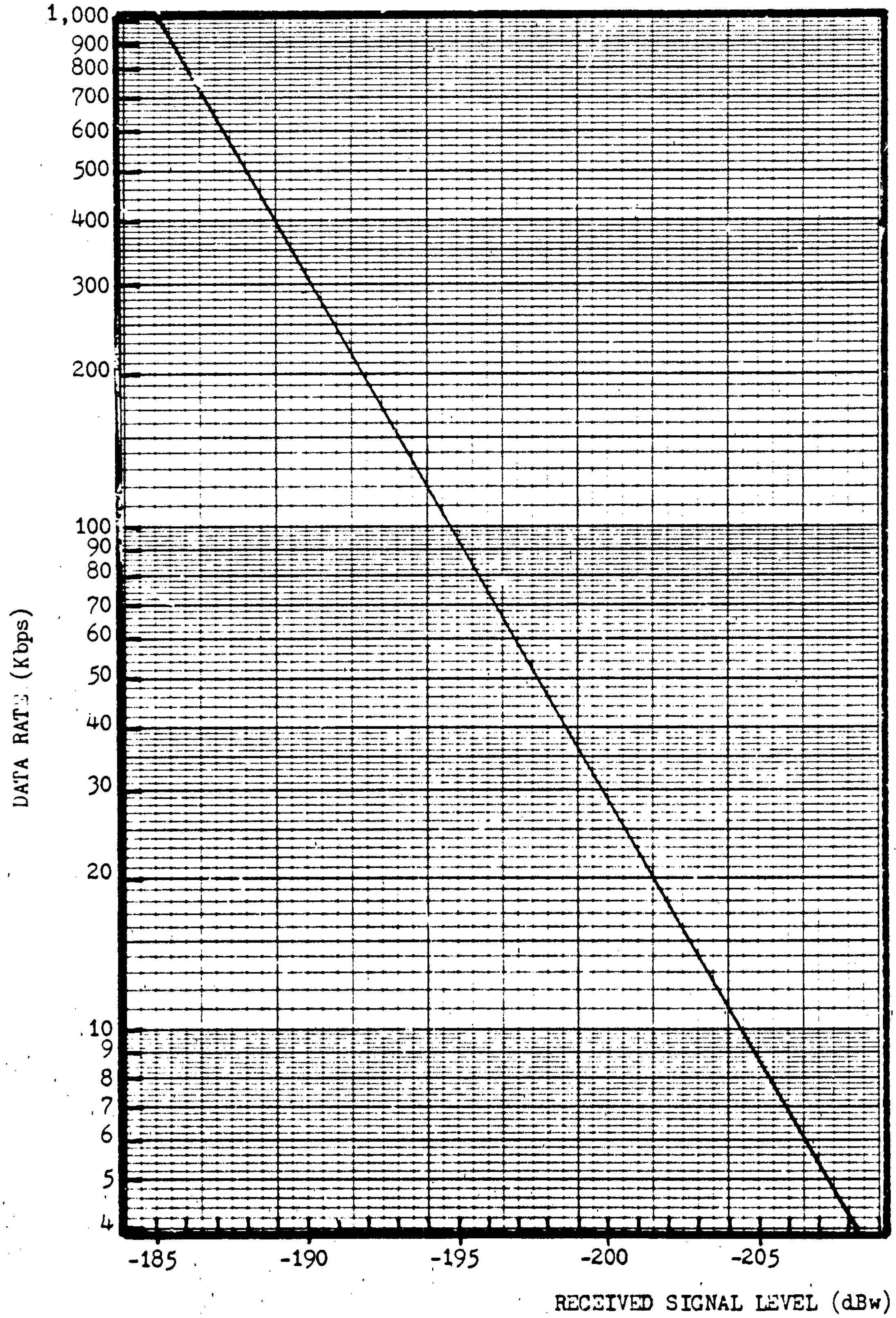


Figure 14. 50 Meter Antenna Performance

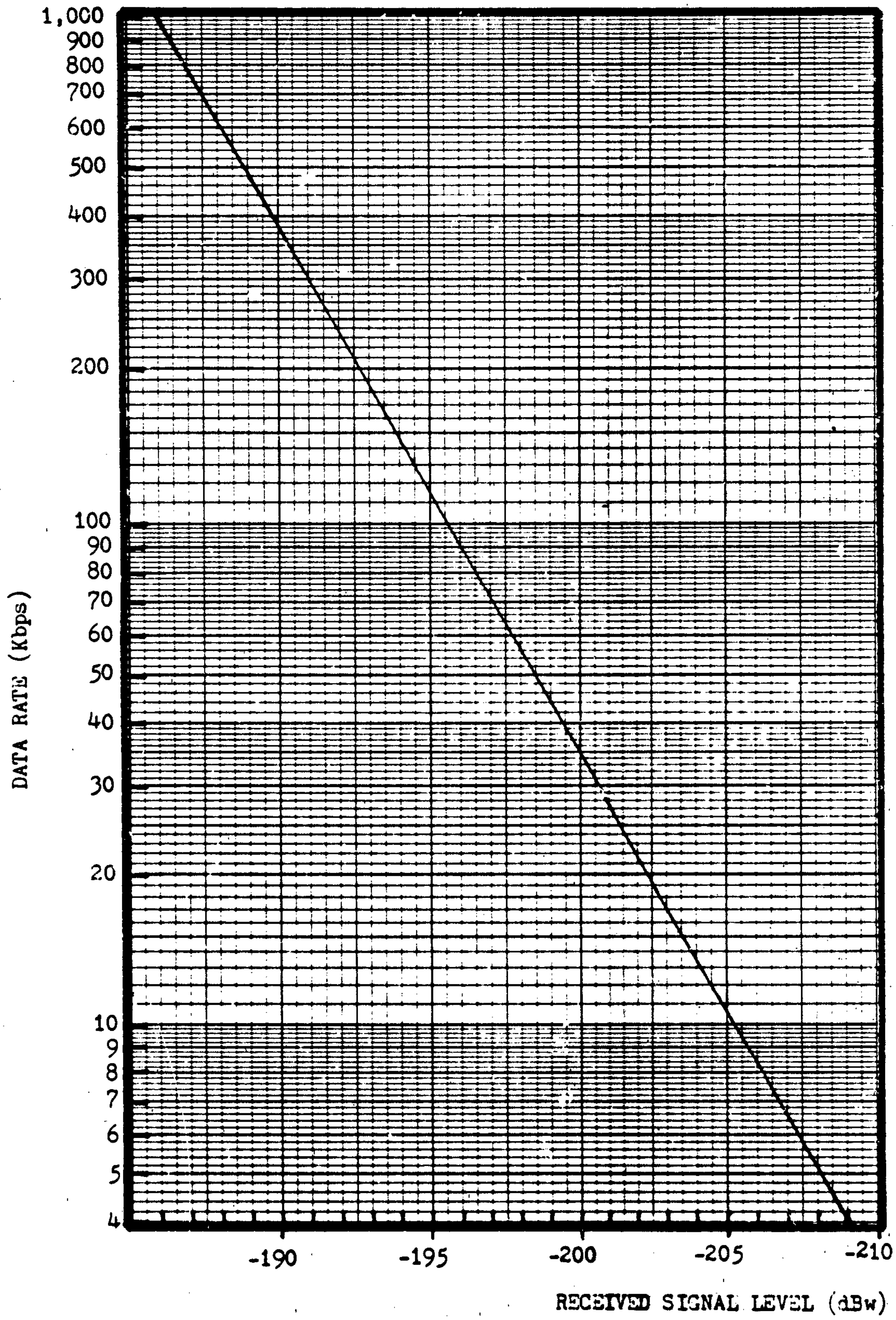


Figure 15. 55 Meter Antenna Performance

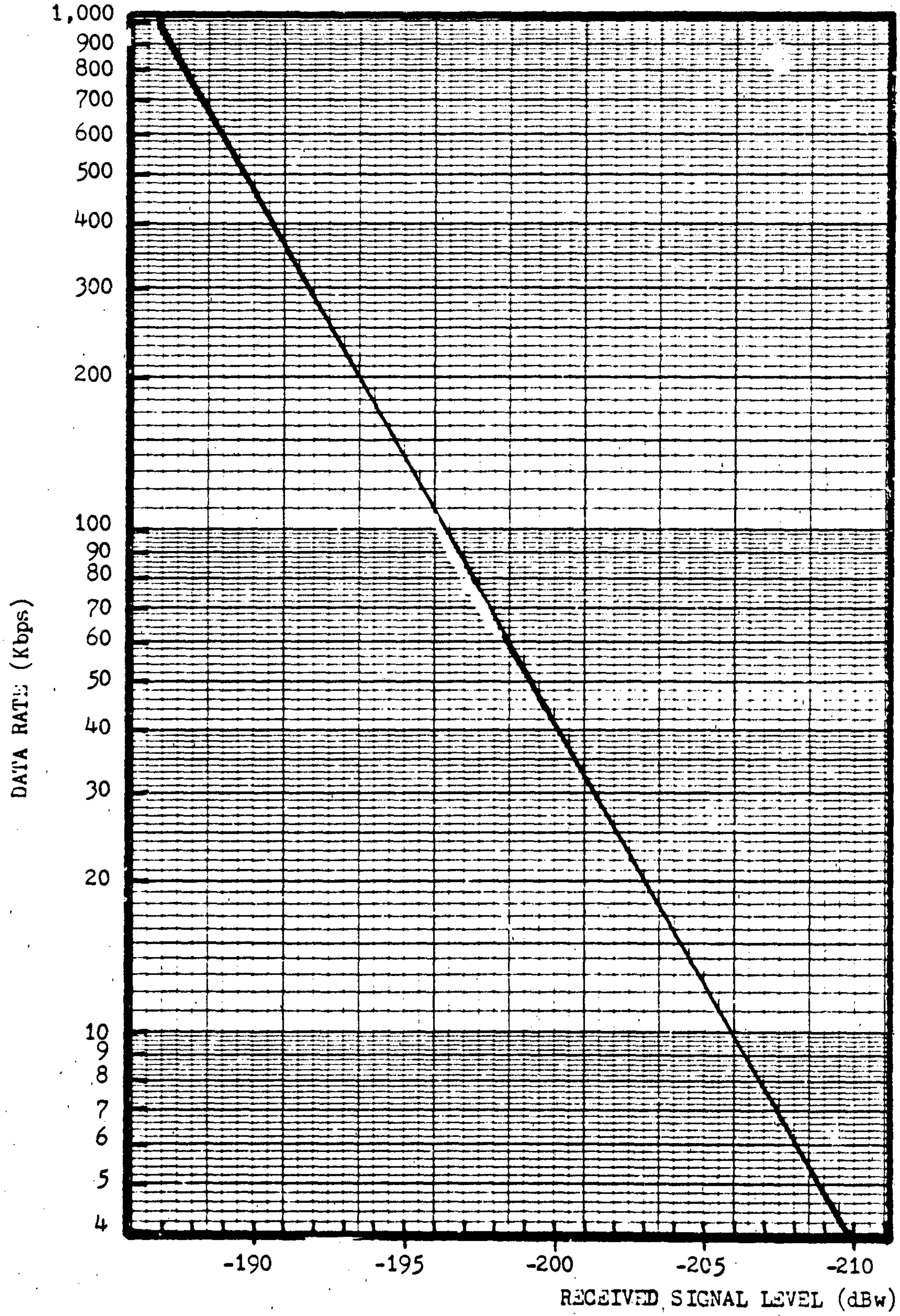


Figure 16. 60 Meter Antenna Performance

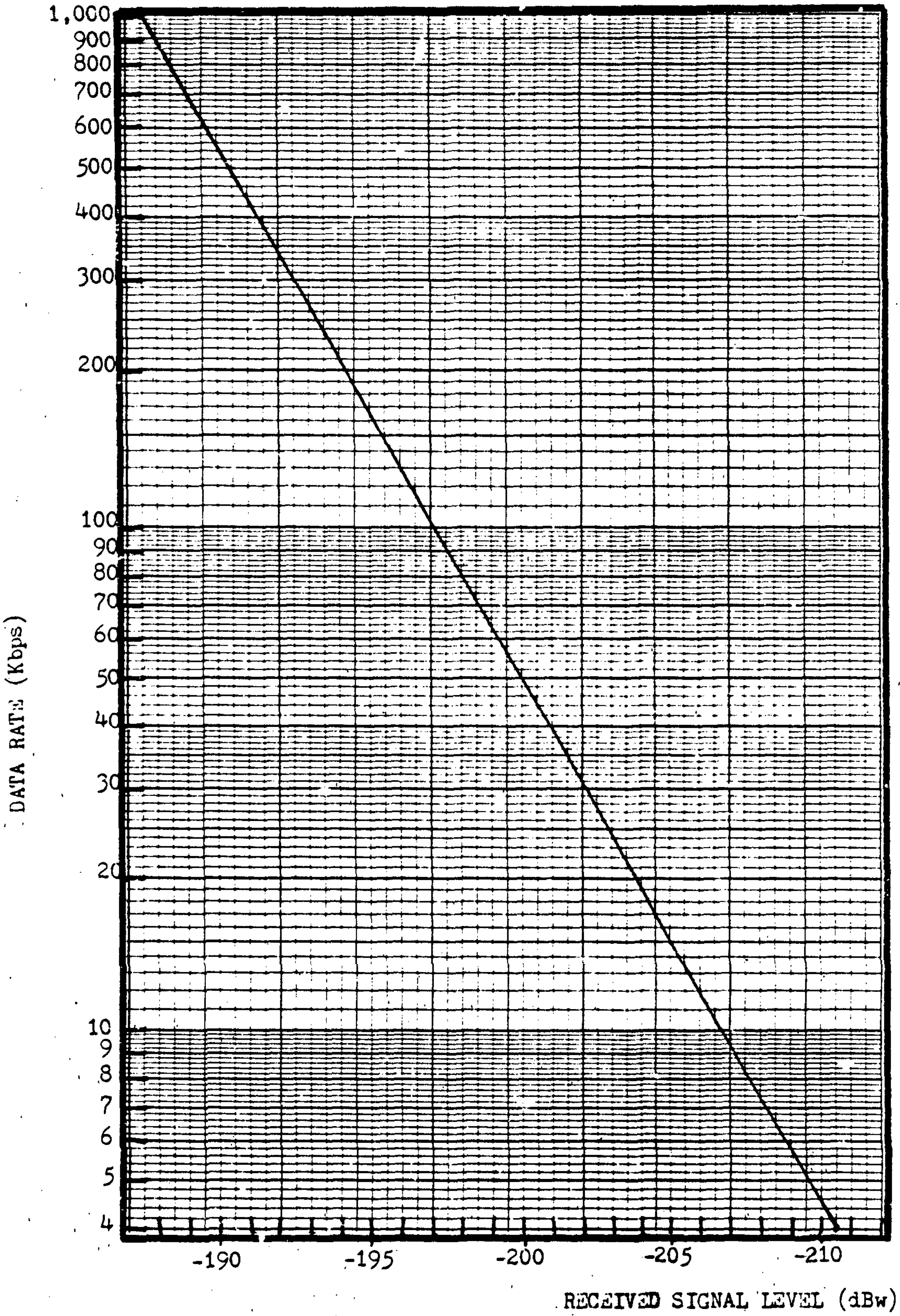


Figure 17. 65 Meter Antenna Performance

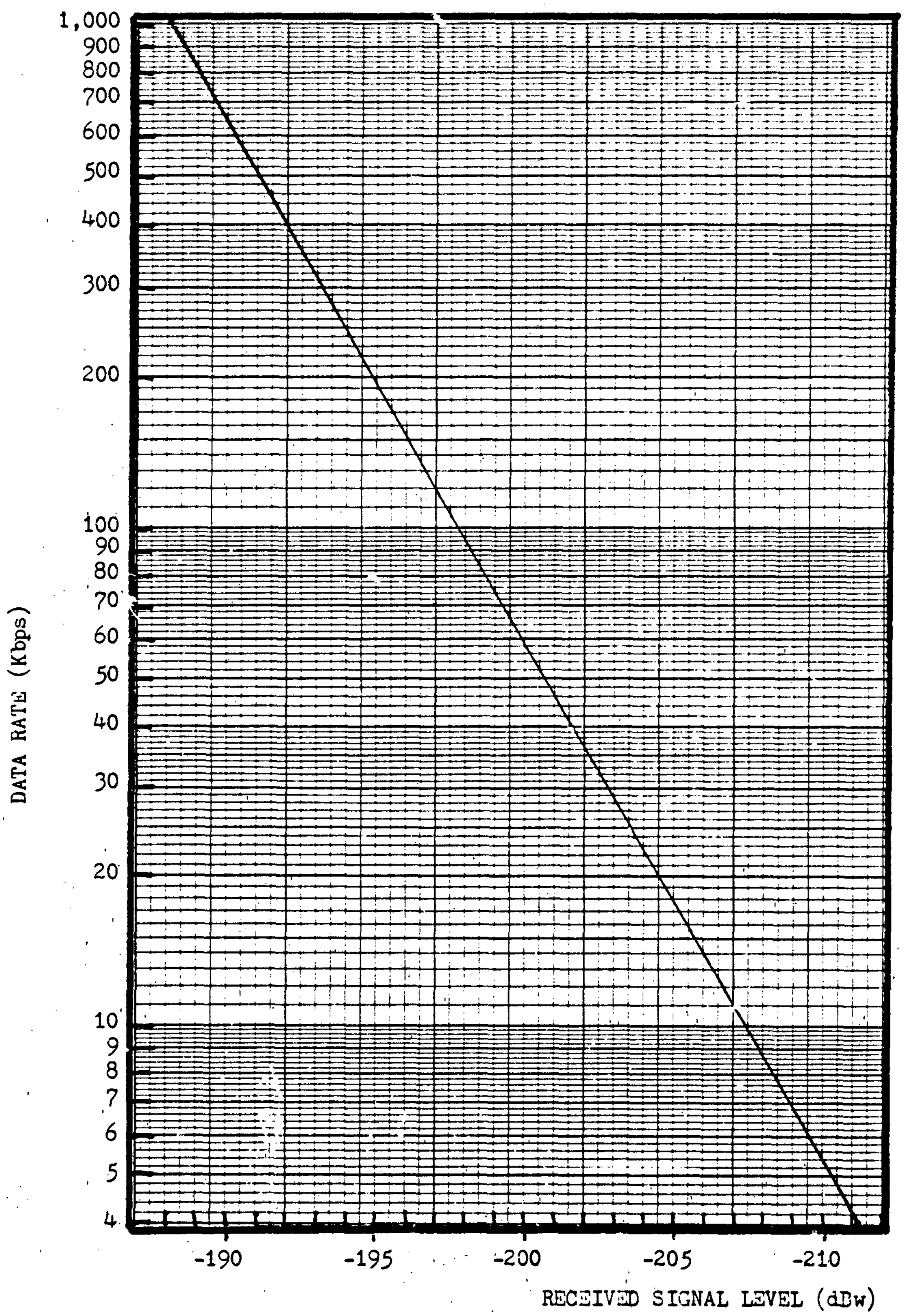


Figure 18. 70 Meter Antenna Performance

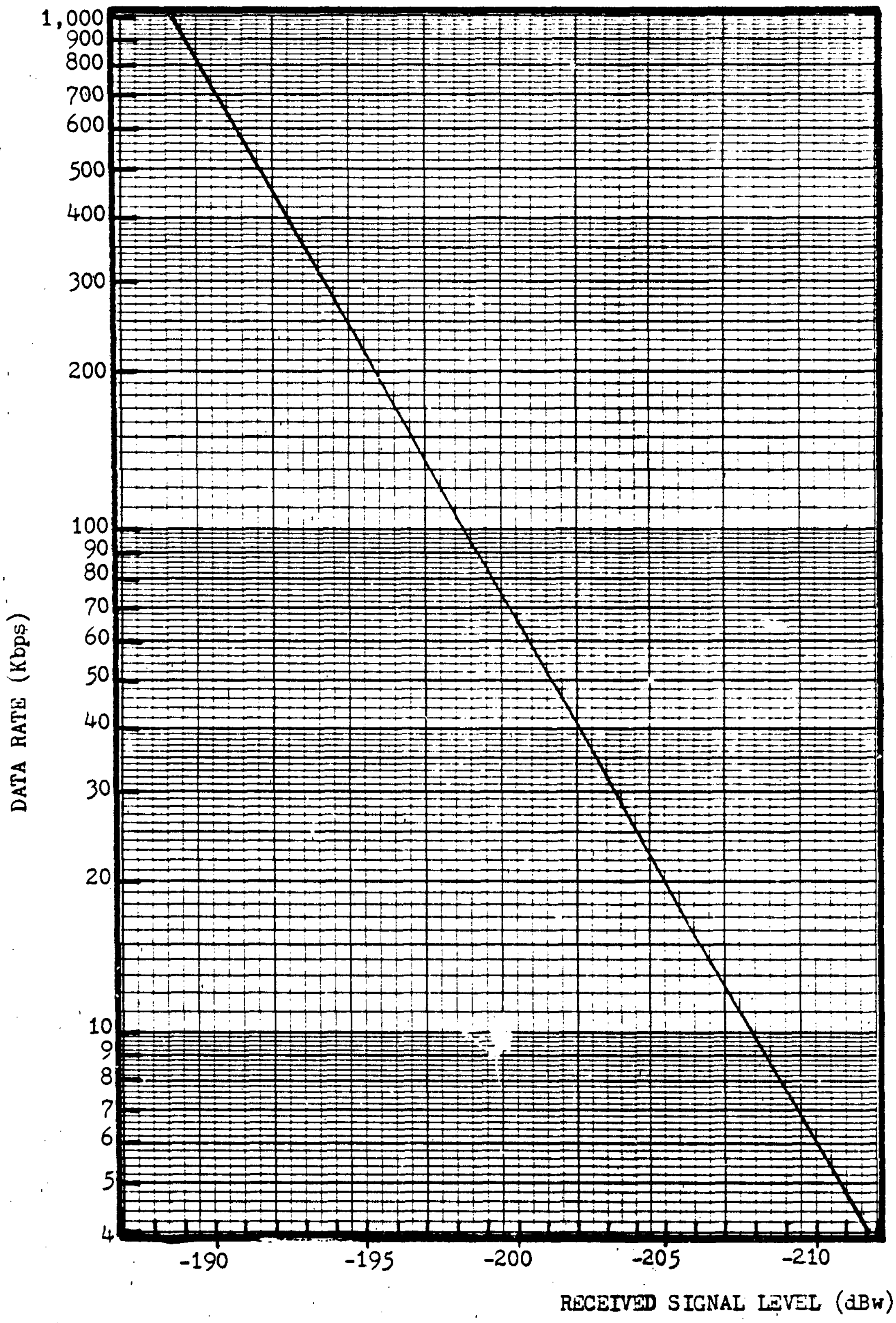


Figure 19. 75 Meter Antenna Performance

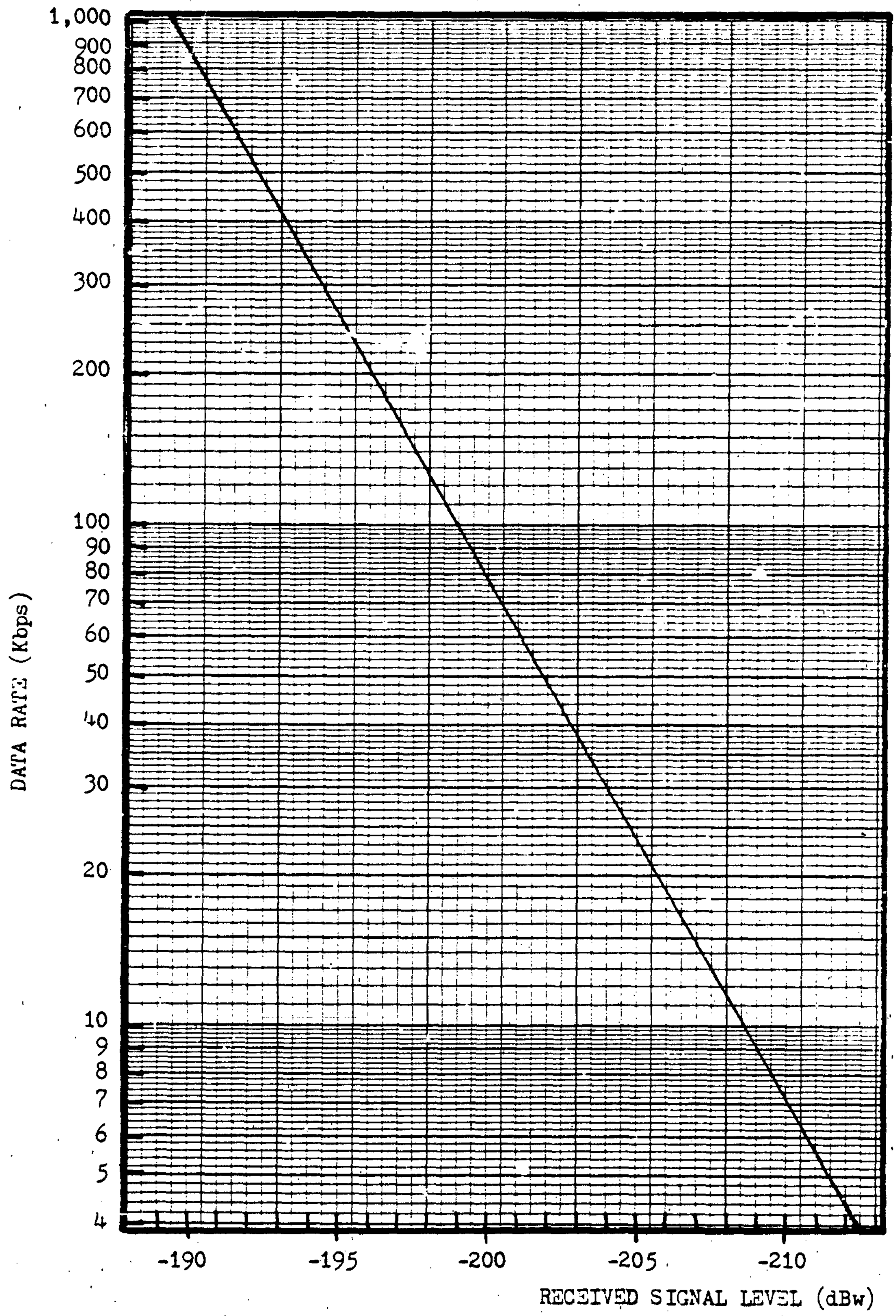


Figure 20. 80 Meter Antenna Performance

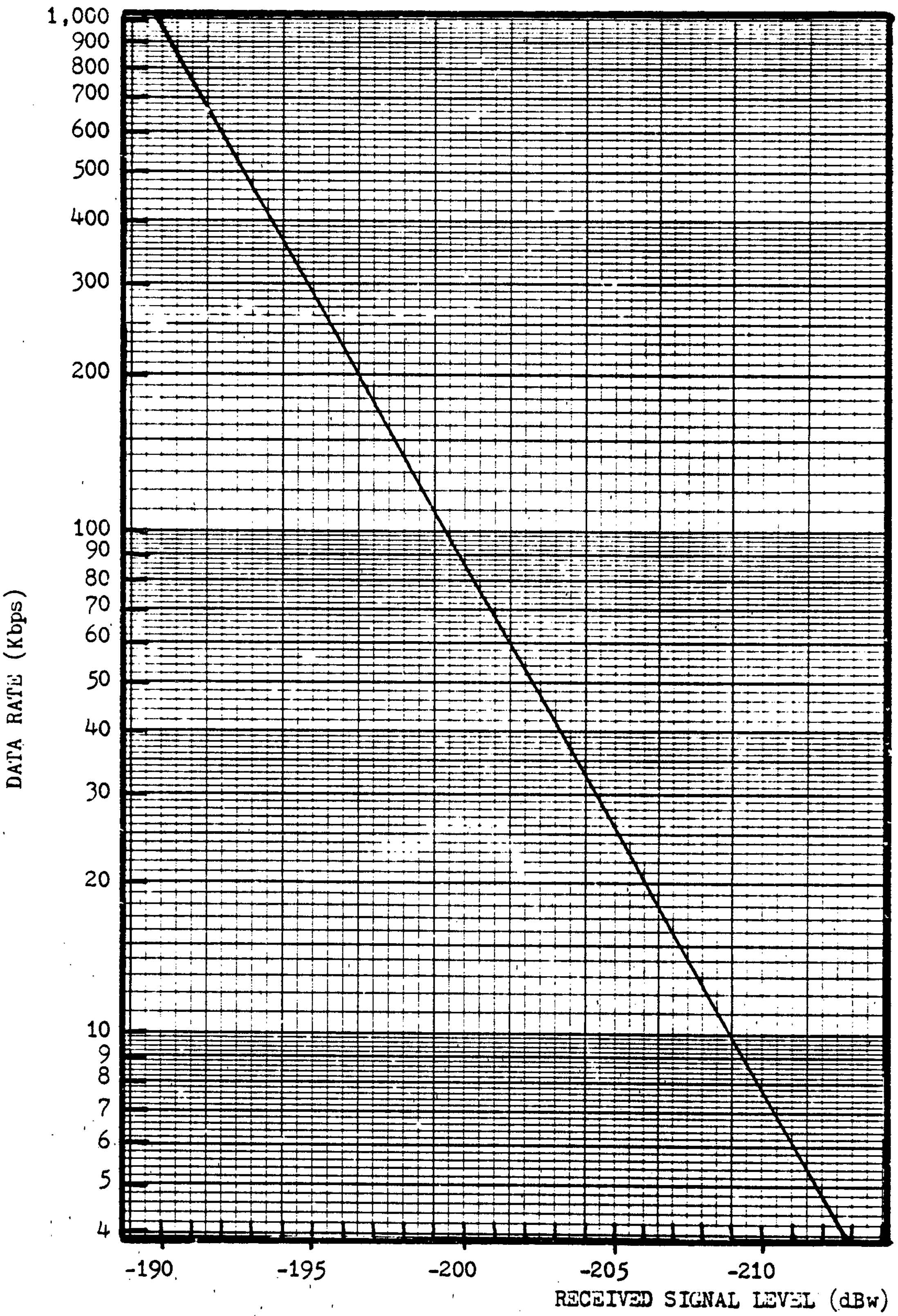


Figure 21. 85 Meter Antenna Performance

Thus, there is a one to one relationship between dB antenna gain and dBw signal level.

The concept of examining the increased gain of an antenna over the TDRS antenna can be put to use in the following equation:

$$\text{Log (bit rate)} = 0.1047 \times (\text{received dBw} + \Delta) + 23.2868 \quad (7)$$

where

Δ = New antenna gain - TDRS antenna gain

Equation (7) is exactly the same as Equation (6) except for the Δ term. By modifying the equation governing the TDRS performance (Equation (6)) it becomes possible to predict the performance of any satellite antenna used in combination with the TDRS receiver. Use of Equation (7) may provide a more accurate estimate of the power necessary to achieve a certain bit rate than estimating numbers directly from Figures 5 thru 21. However, Equation (7) should be regarded only as a rough guideline for planning purposes. There are so many variables involved that it is difficult to arrive at a more accurate estimate without more specific information. For example, the antenna efficiency factor used in gain calculations (Equation (2)) was 40 percent, but it could have easily been 30 percent. This would have reduced the gain of a 30 meter antenna from 53 to 51.8 dB and lowered the bit rate for a given signal strength (Equation (7)). The effect of changing antenna efficiency is examined in Chapter VII. Another unknown is the amount of loss that is inherent to the satellite design (such as the coupling loss between the satellite receiver and the antenna).

Once the limitations on Equation (7)'s accuracy are understood, it can be judiciously used to predict performance. Equation (7)'s predictions will be as valid as the assumptions of the variables used. The major impediment to obtaining an accurate prediction of performance is the fact that variables and equations are so interdependent. (For example, the results of Equation (2) must be placed into Equation (7)). If each variable has a 10 percent uncertainty, the net result will have a much greater uncertainty.

The Reentry Vehicle (RV)

For the sophisticated satellite approach, modifications to the reentry vehicle are minimal. Some minor improvements could be made in the antenna system, however. The gain of the long slot currently used is not very high, and is approximately given by (18:545).

$$10 \text{ Log } \frac{2w}{\lambda} \tag{8}$$

where

w = width of the slot

λ = wavelength of signal

For a typical width of 0.08 m and a frequency of 2260 MHz, the gain is only 0.8 dB. In addition, the 5 watts of transmit power must be split among 3 antennas. The signal strength at the satellite under these conditions would be (from Equation (5)):

$$10 \text{ Log } (5/3) - 190.56 + 0.8 = -187.56 \text{ dBw} \tag{9}$$

This is an exceptionally low signal strength. However, for a 65 meter satellite antenna (see Figure 17 or use Equation (7)), it is possible to achieve a data rate in excess of 1 Mbps. This is without any modifications to existing reentry vehicles. Note that based on Figure 4, a data rate of 4,000 bps could be established between the TDRS and currently unmodified reentry vehicles. However, this is a far too slow data rate.

Although a 65 m diameter parabolic antenna would certainly solve the problem, this is very large for an Earth based antenna, let alone a space antenna. (Recall that the ATS-6 antenna was 9.1 m (6:93) and the TDRS antenna is only 4.9 m in diameter (15:416)). Thus it would be advantageous to increase the gain of the reentry vehicle's signal, thereby reducing the required size of the satellite's receiving antenna.

A simple improvement would be to have a higher gain antenna, such as a monopole or dipole, protrude from the base of the reentry vehicle. Some reentry vehicles already have an antenna protruding from their base (see Figure 3). One advantage to this approach is that all five watts of transmit power would be dedicated to one antenna. There may be less coupling loss between the transmitter and one antenna than with three antennas. If a dipole antenna is used, and it provides (as discussed in Chapter II) 2.148 dB gain, then from Equation (5) the signal strength at the satellite would be:

$$10 \text{ Log } (5) - 190.56 + 2.148 = -181.4 \text{ dBw} \qquad (10)$$

From Figure 10, or Equation (7), it can be shown that a 30 meter satellite antenna would allow a data rate of approximately 748 Kbps for this received signal strength. Thus, with slight improvement in the reentry vehicle's antenna system and no increase in transmit power (increasing power and frequency are discussed in Chapter VII), an acceptable data rate can be obtained with a 30 meter, 40 percent efficient, antenna. Since the required satellite antenna diameter can be cut in half by a modest improvement in reentry vehicle antenna gain and devoting RV transmitter power to one antenna instead of three, it may be most practical to modify the current reentry vehicle design, even if there are many reentry vehicles and only one satellite.

<u>Analysis</u>

If the sophisticated satellite approach is taken, a cost versus benefit analysis must be performed to determine the optimum combination of improvements to the satellite and reentry vehicle. As described earlier, the first space test deployment of a section of a 55 meter antenna is approximately four years away. This antenna design could be scaled up to 85 meters, however the added cost, weight (can it be launched), and design time are all unknowns. These three factors must be balanced against the cost of modifying the reentry vehicles. The design time and additional weight due to modifying an RV would probably be minimal. The cost of modifying an RV would probably be small as well. However, which would be more expensive over the five to ten year life of the satellite: redesigning many reentry vehicles, or a one time modification and launch of a very large space antenna? After the RV design change is implemented, is the new RV more, less, or just as expensive to manufacture than the old RV?

It is possible to achieve an acceptable data rate using a variety of satellite antennas and minor reentry vehicle modifications. So far, the performance of 17 different satellite antennas have been examined. The required data rate will dictate the required receive signal level for each antenna. This in turn determines how much gain the reentry vehicle's antenna must provide, and how much modification to the RV is required. The cost versus benefit analysis mentioned earlier is proposed in Chapter VIII as an area for further study.

V. The Sophisticated Reentry Vehicle Approach

The Reentry Vehicle (RV)

The second approach to establish a data link between a reentry vehicle and a satellite is to drastically increase the level of sophistication of the RV. Two different RV orientations are considered in this chapter, since the characteristics of reentry vehicles are always subject to change. In this section, the attitude of the RV is assumed to be constantly changing throughout the flight. This is usually not the orientation of current reentry vehicles. The second and more prevalent case of a constant RV pitch angle is discussed in the following section.

Figures 22 and 23 show one possible design for the case of changing attitude in its stowed and deployed configurations. A single 14 cm diameter parabolic dish antenna is used to transmit all of the telemetry. As stated previously, the total data rate of a reentry vehicle could reach 1 Mbps.

The choice of 14 cm as the diameter of the antenna is arbitrary. In this case it is approximately one third of the 40 cm base of the reentry vehicle. A major factor in determining how large this antenna can be is its structural integrity. The antenna must be able to survive the vibration, air turbulence, and thermal effects associated

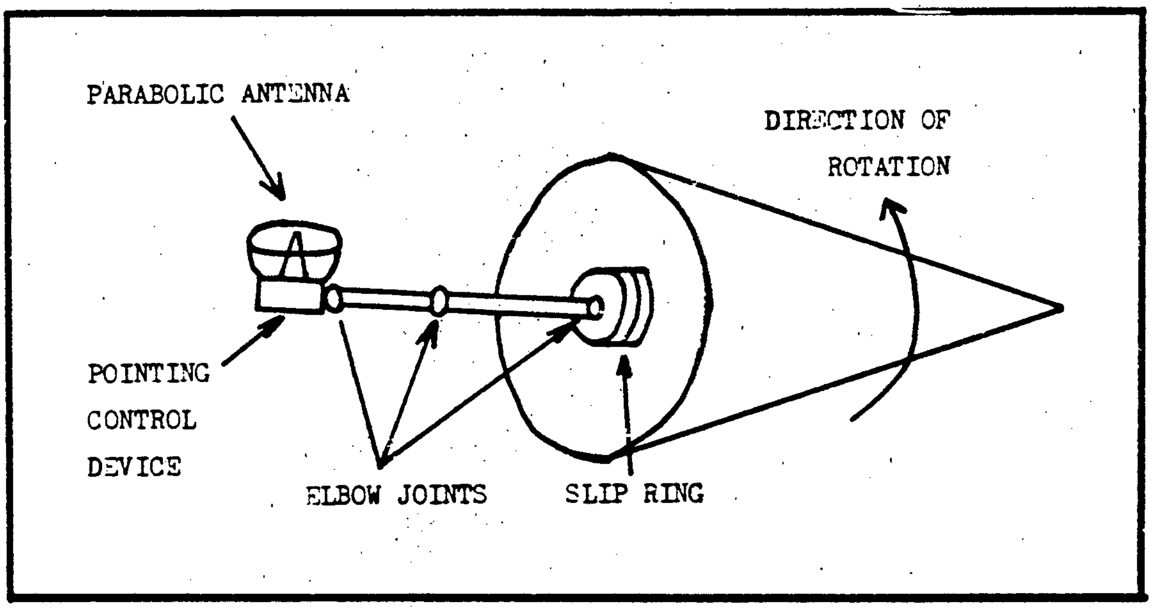


Figure 22. Proposed Sophisticated Reentry Vehicle Deployed Configuration (angled view)

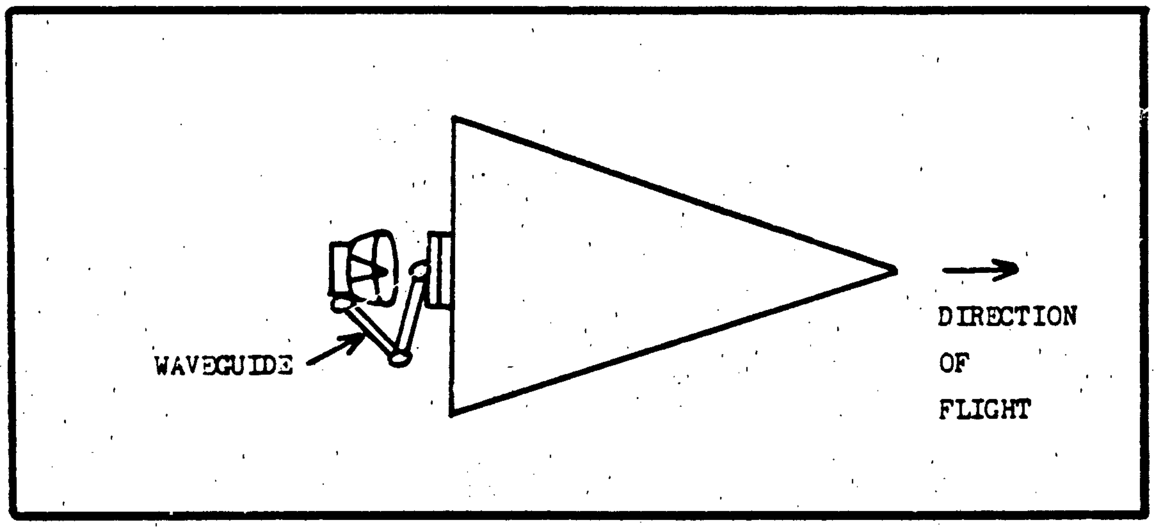


Figure 23. Proposed Sophisticated Reentry Vehicle Stowed Configuration (side view)

with reentering the Earth's atmosphere. The reentry vehicle structure in front of the antenna acts as a shield against these effects. The larger the antenna, the greater the intensity of reentry effects on it. A separate analysis should be performed to determine what the maximum diameter could be without risking structural damage to the antenna system (this is recommended for further study in Chapter VIII).

The proposed antenna will be much more directional than the dipole of the previous chapter, having a 3 dB beamwidth of 66 degrees at 2260 MHz (using Equation (3)). One disadvantage of the narrower beamwidth is that ground tracking stations will no longer be able to pick up the telemetry signal. Of course, the purpose of having a relay satellite is to eliminate the need for ground tracking stations. However, it would be a prudent bonus to have a backup telemetry receiving capability in the event of satellite failure.

The primary disadvantage of using a more directional antenna is the necessity for accurate pointing toward the satellite. As shown in Figure 22, a pointing control device would be required to change the position of an elbow joint. Rotation of the joint would, in turn, rotate the antenna. Since reentry vehicles typically rotate for stabilization, a slip ring would be necessary at the base of the RV. The slip ring couples the rotating wave guide inside the RV to a nonrotating wave guide leading to the antenna.

The proposed antenna system would involve the use of two motors, each manipulated by the pointing control device. A motor inside the slip ring turns the antenna-wave guide combination in the opposite direction of reentry vehicle rotation, effectively reducing the antenna rotation rate to zero. A motor located directly behind the antenna controls the position of the last elbow joint. By manipulating these motors the pointing device can aim the antenna in virtually every direction.

Thus, the complexity of the system is vastly increased over the minor changes in the previous chapter. There are mechanical problems such as deploying the antenna, maintaining structural integrity through reentry, and the use of small, light weight, and yet precise motors. Then there are the electrical control problems to consider. The satellite will have to emit a beacon signal for the reentry vehicle to lock on to. The pointing device must determine the proper commands to send to the motors, based on the strength of the received beacon signal. A microcomputer may be necessary inside the pointing control device to make decisions and send commands.

On the positive side, the wide 3 dB beamwidth of the reentry vehicle antenna (66 degrees) significantly reduces the required pointing accuracy. The antenna could be as much as 33 degrees off target without a noticeable degradation in performance. Also, the rate at which the antenna position needs to be changed is very slow since the receiving satellite is approximately 35,700 km away. Table 2 illustrates this point.

In Table 2, the look angle is defined as the angle between the Earth horizon and the geosynchronous orbit satellite. The horizon in the direction of reentry vehicle travel is 0 degrees. A vertical line perpendicular to the Earth's surface is 90 degrees. The antenna pointing angle in Table 2 is defined as the angle of the reentry vehicle transmit antenna relative to the cone shaped body of the reentry vehicle. When the antenna is pointed toward the base of the reentry vehicle the antenna is at an angle of 0 degrees. When the antenna is pointed directly away from the reentry vehicle, and in the opposite direction of RV travel, the antenna is at 180 degrees.

Table 2

Reentry Vehicle Antenna Pointing Angles

RV Travel Distance (km)	Look Angle (degrees)	RV Antenna Pointing Angle (degrees)
0	83.6	18.6
4,000	90.0	90.0
8,000	96.4	171.4

From the start to the termination of telemetry transmission, the reentry vehicle is continuously changing attitude (17:182) and may undergo as much as a 140 degree change in pitch. The tip of the reentry vehicle cone is typically pointed away from the Earth during the ascent stage and toward the Earth during the descent stage. For the antenna pointing angles given in Table 2, it was assumed that when the RV was ejected from the missile, the angle of the nose cone relative to the Earth horizon was 65 degrees. If the distance travelled by the reentry vehicle is approximately 8,000 km and the satellite is 35,700 km above the halfway point of the RV's trajectory, then the look angle at launch is given by:

$$\text{Look Angle } \psi = \tan^{-1}\left(\frac{35{,}700}{4{,}000}\right) = 83.6 \text{ degrees} \tag{11}$$

If the reentry vehicle's pitch did not change during flight, the total change in antenna pointing angle would be 12.8 degrees. However, the reentry vehicle may undergo a change in pitch of as much as 140 degrees, making the total change in antenna pointing angle 152.8 degrees. If the average speed of the reentry vehicle is 3,300 meters per second, it would take the RV approximately 40 minutes to travel 8,000 km. This implies that the reentry vehicle antenna would have to be moved at a rate of 3.8 degrees per minute throughout the flight to track the satellite.

The slow antenna pointing rate of 3.8 degrees per minute, combined with the antenna beamwidth of 66 degrees significantly relaxes the required performance of a pointing control device. As an alternative to a sophisticated pointing control device, a simple timing mechanism may provide sufficient pointing accuracy. The timing mechanism would be preprogrammed to change the antenna position by a certain amount during the flight. The preprogramming would be based on the location of the satellite and the planned flight path of the reentry vehicle. Some of the advantages of a timing mechanism over a pointing control device are elimination of the need for a satellite beacon and a controlling microcomputer aboard the RV. One disadvantage is that any anomaly causing a reentry vehicle to significantly deviate from its preprogrammed flight path would also cause a loss of telemetry.

After all this effort, how much gain is actually achieved? From Equation (2), the gain of a 14 cm parabolic antenna is:

$$10 \text{ Log}\left[\left(\frac{\pi(0.14)}{0.133}\right)^2 (0.4)\right] = 6.4 \text{ dB} \qquad (12)$$

for 2260 MHz and assuming 40 percent efficiency. This is an improvement of only 4.2 dB over the much more modest dipole antenna proposed in the previous chapter. Thus the benefit of a significant increase in the level of sophistication does not appear to justify the cost. Your judgement should be reserved, however, until the analysis section of this chapter.

Constant RV Pitch Simplifies Problem

As stated previously, the total change in antenna pointing angle would be only 12.8 degrees if the pitch of the reentry vehicle did not change during the course of its flight. Thus it is appropriate to consider the advantages of the currently used method of maintaining a relatively constant RV pitch throughout the flight. Immediately upon separation from the booster, the reentry vehicle could rotate until the nose of the RV is in the proper attitude for reentry. The RV would remain in this attitude throughout its entire trajectory (17:208). Figure 24 illustrates this point.

The 14 cm transmit antenna would be rigidly bolted onto the base of the RV. Recall that the RV antenna has a 3 dB beamwidth of 66 degrees. This should be more than sufficient to allow for small errors in reentry vehicle pitch as well as the 12.8 degree change in the look angle as the RV moves across the Earth's surface. Note in Figure 24 that the 66 degree beamwidth is sufficient to allow continuous reception of the telemetry signal, even if the reentry point is half way around the world from the booster separtion point. The orbital position of the satellite must be confined to a small section of the geosynchronous orbit in order to continuously

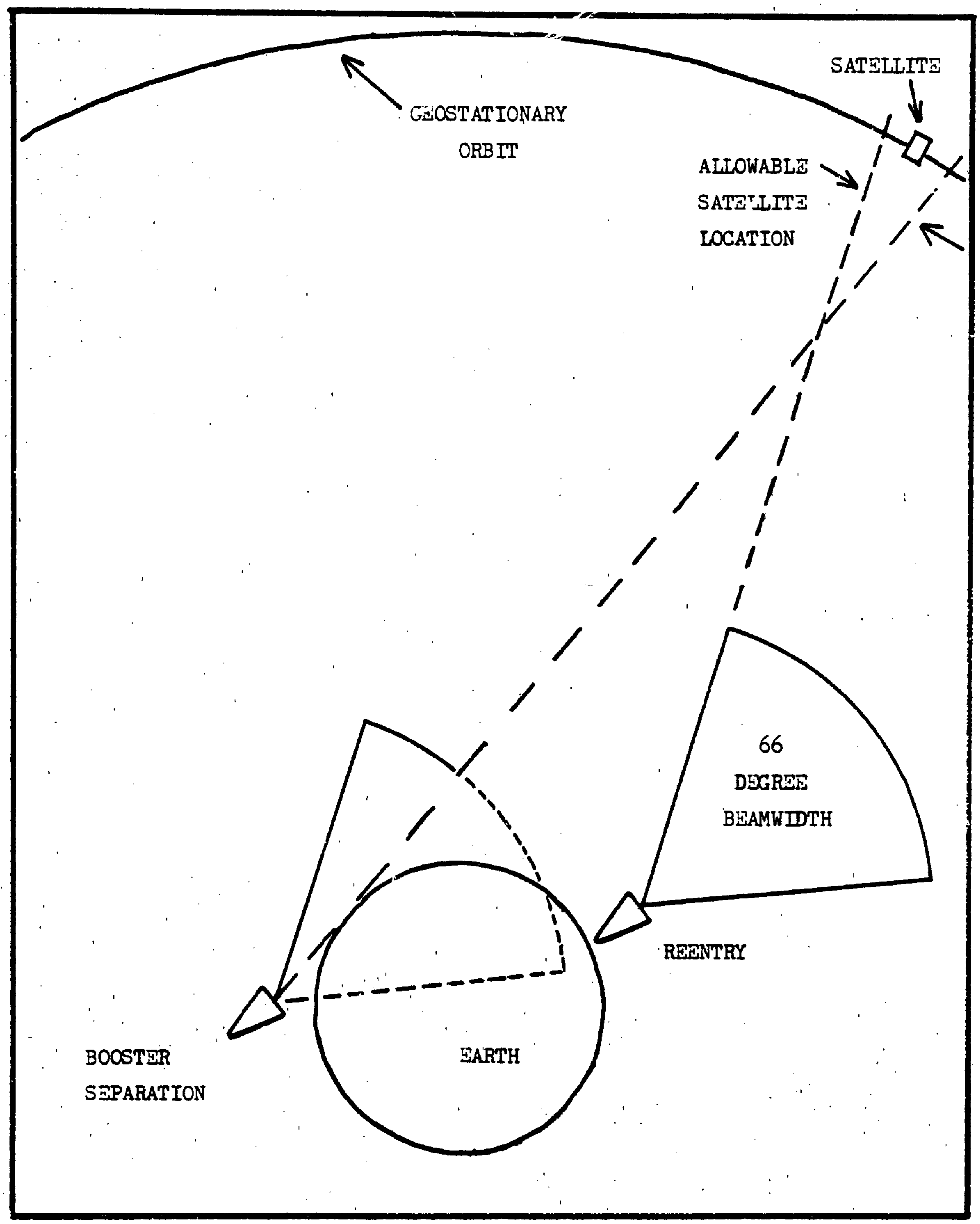


Figure 24. Reentry Vehicle Pointing

remain in line of sight with the reentry vehicle. As the reentry angle of the RV becomes steeper, the allowable variation in satellite location becomes smaller.

Fastening the 14 cm antenna to the base of the reentry vehicle would significantly reduce the sophistication of the RV depicted in Figures 22 and 23 without affecting data rate performance. The rotation of the RV and all the other problems involved in pointing the reentry vehicle antenna at the satellite would be eliminated.

The Satellite

The primary effect of increasing the gain of the reentry vehicle antenna is to reduce the required physical size of the satellite antenna. This is highly desirable, since a smaller antenna would decrease the satellite's size and weight (making it less expensive to place the satellite in orbit). It would also probably decrease the cost of the satellite.

Given a reentry vehicle antenna gain of 6.4 dB, the received signal level at the satellite would be (from Equation (5)):

$$10 \text{ Log } (5) - 190.56 + 6.4 = -177.2 \text{ dBw} \qquad (13)$$

Again, a frequency of 2260 MHz is assumed. A five watt transmitter is assumed so the results can be compared with the dipole of the previous chapter.

Compare the -177.2 dBw signal level to the received signal level if a reentry vehicle dipole antenna is used (previously calculated in Equation (10)):

$$10 \text{ Log } (5) - 190.56 + 2.148 = -181.4 \text{ dBw} \qquad (10)$$

Thus an improvement of 4.2 dBw is obtained due to the 4.2 dB increase in reentry vehicle antenna gain. Recall that in Chapter IV it was shown that a 1 dB increase in satellite antenna gain allowed the same data rate to be achieved with a 1 dBw weaker received signal. The conclusion then is that adding 1 dB gain to the satellite antenna has the same result as adding 1 dB to the reentry vehicle gain. Thus, it does not matter which end of the telemetry link receives the additional gain, as the performance will be the same.

It follows then that improving the reentry vehicle gain by 4.2 dB will reduce the required satellite antenna gain for a specific data rate by 4.2 dB. This in turn will reduce the required antenna diameter.

The amount of reduction in satellite antenna diameter can be obtained by using the results in Table 1 of Chapter IV. Note that doubling the antenna diameter results in a 6 dB increase in gain. For example, a 5 meter antenna has 37.5 dB gain and a 10 meter antenna has a 43.5 dB gain; a 15 meter antenna has a 47 dB gain and a 30 meter antenna has a 53 dB gain, etc. The amount of antenna diameter reduction due to a 4.2 dB reduction in gain can be calculated by selecting an antenna from Table 1 at random, subtracting 4.2 dB gain, and then using Equation (2) to find the new antenna diameter. For example, using a 10 meter antenna:

$$43.5 - 4.2 = 10 \text{ Log}\left[\left(\frac{\pi d}{0.133}\right)^2 (0.4)\right]$$

$$103.93 = \left[\left(\frac{\pi d}{0.133}\right)^2 (0.4)\right]$$

$$145.87 = \frac{\pi d}{0.133}$$

$$d = 6.18 \text{ meters} \qquad (14)$$

The new diameter of 6.18 meters is 61.8 percent of the original antenna's diameter. Similar results are obtained when other antenna gains are used in Equation (2). Thus, for a 40 percent efficient antenna, a 4.2 dB increase in reentry vehicle antenna gain would result in a satellite antenna 61.8 percent the size of the original antenna.

Analysis

At the end of the reentry vehicle section of this chapter, it was stated that the 4.2 dB increase in gain over the dipole proposed in Chapter IV might not justify the expense of increasing the sophistication of the reentry vehicle. In order to determine if the expense is justified, it is necessary to compare the expense to the cost saved on the satellite.

Table 3 shows the 61.8 percent reduction in required satellite antenna size due to increased reentry vehicle gain from 2.2 to 6.4 dB. Note that for a 5 meter antenna, a reduction of 1.91 meters is obtained. This reduction is not significant. For this size antenna, neither the weight nor its physical dimensions pose a problem for launching the antenna aboard the Space Shuttle. Also the cost savings in producing an antenna 1.91 meters smaller should be negligible. For an 85 meter antenna, however, the reduction in size of 32.47 meters becomes significant in terms of weight, available space in the Space Shuttle cargo bay, and manufacturing and launch costs.

Table 3

Satellite Antenna Reduction Due To Increased Reentry Vehicle Antenna Gain

Satellite Antenna Diameter (m)	New Diameter Given 4.2 dB Added RV Antenna Gain (m)	Reduction in Satellite Antenna Size (m)
5	3.09	1.91
10	6.18	3.82
15	9.27	5.73
20	12.36	7.64
25	15.45	9.55
30	18.54	11.46
35	21.63	13.37
40	24.72	15.28
45	27.81	17.19
50	30.90	19.10
55	33.99	21.01
60	37.08	22.92
65	40.17	24.83
70	43.26	26.74
75	46.35	28.65
80	49.44	30.56
85	52.53	32.47

The cost savings of a satellite with a smaller antenna occurs once, while the added expense of manufacturing a reentry vehicle more sophisticated than the one proposed in the previous chapter occurs perhaps thousands of times over the lifetime of the satellite. An analysis of the cost savings of reduced antenna size versus increased reentry vehicle cost is recommended in Chapter VIII. This analysis differs slightly from the analysis mentioned in Chapter IV. There, the analysis concerns whether or not any RV modification should be made at all. Any reentry vehicle modification would be minimal, with RV antenna gains ranging from 0 to 2.2 dB. In this chapter, the analysis being proposed is an evaluation of just the increase in cost of a sophisticated reentry vehicle over and above the cost of the modest changes proposed in Chapter IV. Note that the reductions of satellite antenna size in Table 3 are based on the added gain of a 14 cm parabolic antenna over the dipole of Chapter IV, not the current reentry vehicle configuration of cavity backed slot antennas.

VI. Comparison of Approaches

The most conservative course of action in pursuing the investigation of a reentry vehicle to satellite telemetry link would be to perform further analysis on the sophisticated satellite approach first. After this analysis is complete, the advantages and disadvantages of increasing reentry vehicle sophistication should become clearer. A decision can then be made as to whether a sophisticated reentry vehicle should be analyzed in detail. The cost of manufacturing many sophisticated reentry vehicles appears to be much higher than modifying one satellite. Also it should be noted that reentry vehicles are expendable items. Even test RVs without a warhead are usually used only once. There is not much incentive to spend more than the absolute minimum on a device whose operational lifetime is only approximately 40 minutes.

However, a person's approach to the problem may depend largely on his or her point of view. For example, some readers of this thesis may have set a goal of developing a very sensitive satellite with a large antenna. The development of such a satellite would require extensive justification. The data in Chapter IV would provide some of the supporting arguments for a sophisticated satellite. On the other hand, some readers may be interested solely in researching possible future designs of reentry vehicles. Both Chapters IV and V provide some ideas of where RV design could lead.

The best approach to take is not always the easiest or cheapest, and the reader's point of view will be one of the main factors in deciding which approach to take.

VII. Other Variables

Transmit Power

The effect of increasing transmit power can be found by using the received signal strength equation (Equation (5)) and the performance equations (Equation (6) or (7)). For 5 watts of transmitting power at 2260 MHz, the received signal strength at the satellite has previously been shown to be (for a reentry vehicle with a dipole antenna):

$$10 \text{ Log } (5) - 190.56 + 2.148 = -181.4 \text{ dBw} \qquad (10)$$

Using Equation (6), the bit rate for the TDRS at this level of strength is:

$$\text{Log (bit rate)} = 0.1047\,(-181.4) + 23.2868$$

$$\text{bit rate} = 19{,}700 \text{ bps} \qquad (15)$$

This is the bit rate for a 4.9 meter satellite antenna and a 5 watt transmitter. If the transmit power of the reentry vehicle is increased to 10 watts the received signal level would be:

$$10 \text{ Log } (10) - 190.56 + 2.148 = -178.4 \text{ dBw} \qquad (16)$$

As expected, doubling the transmit power has increased the received signal level by 3 dB. The resulting bit rate is:

$$\text{Log (bit rate)} = 0.1047\ (-178.4) + 23.2368$$

$$\text{bit rate} = 40{,}580 \qquad (17)$$

Thus, doubling the transmit power has the effect of increasing the maximum allowable bit rate (for a 1×10^{-5} bit error rate) from 19,700 to 40,580, a 106 percent increase. Table 4 lists the bit rates for various power levels. All values are based on a simple dipole antenna for the reentry vehicle. Note that increasing the transmit power from 10 watts to 20 watts also results in a 106 percent increase in the bit rate. Thus, doubling the transmit power slightly more than doubles the bit rate.

Table 4

Effect of Increasing Transmit Power on Bit Rate Using a 4.9 Meter Satellite Antenna

Transmit Power (watts)	Maximum Bit Rate (bits per second)
5	19,700
10	40,580
15	61,863
20	83,606
25	105,610
30	127,823
35	150,211
40	172,751

The primary advantage of increasing reentry vehicle transmit power is the reduction in the required gain of the satellite antenna. This reduction in gain would allow a significant reduction of the diameter of the antenna. It has just been shown that doubling the transmit power will increase the received signal strength by 3 dB. Similarly, increasing the reentry vehicle antenna gain by 3 dB would also increase the received signal strength by 3 dB. It has previously been shown that a 1 dB increase in reentry vehicle antenna gain has exactly the same effect as increasing the satellite antenna gain by 1 dB. Thus, doubling the transmit power, or increasing either the satellite or reentry vehicle antenna gain by 3 dB would have exactly the same effect on the maximum allowable bit rate for the telemetry link. This leads to the conclusion that doubling the transmit power would allow a 3 dB reduction in satellite antenna gain while still maintaining the same bit rate.

Figure 25 shows the effect of increasing transmitter power on the required satellite antenna diameter for bit rates of 1.0 and 0.5 Mbps. As expected, a lower bit rate shifts the curve to the left. The curve is also slightly steeper for a lower bit rate. The actual numbers for the 1.0 Mbps data are listed in Table 5. The required satellite antenna diameter is calculated through the use of Equations (2), (5), and (7). First, Equation (5) is used to calculate received signal level given a specific transmit power. For example, in Equation (10) the received signal level for a 5 watt transmitter was calculated to be -181.4 dBw. Next, the required satellite antenna gain must be calculated from Equation (7). However, for this purpose it is most useful to rearrange Equation (7) as follows:

$$\text{Log (bit rate)} = 0.1047 \times (\text{rec dBw} + \Delta) + 23.2868 \qquad (7)$$

$$\text{Log } (1 \times 106) = 0.1047 \text{ (rec dBw)} + 0.1047 (g - 37.3) + 23.2868$$

$$-17.2868 - 0.1047 \text{ (rec dBw)} = 0.1047g - 3.9053$$

$$-127.8 - \text{(rec dBw)} = g \qquad (18)$$

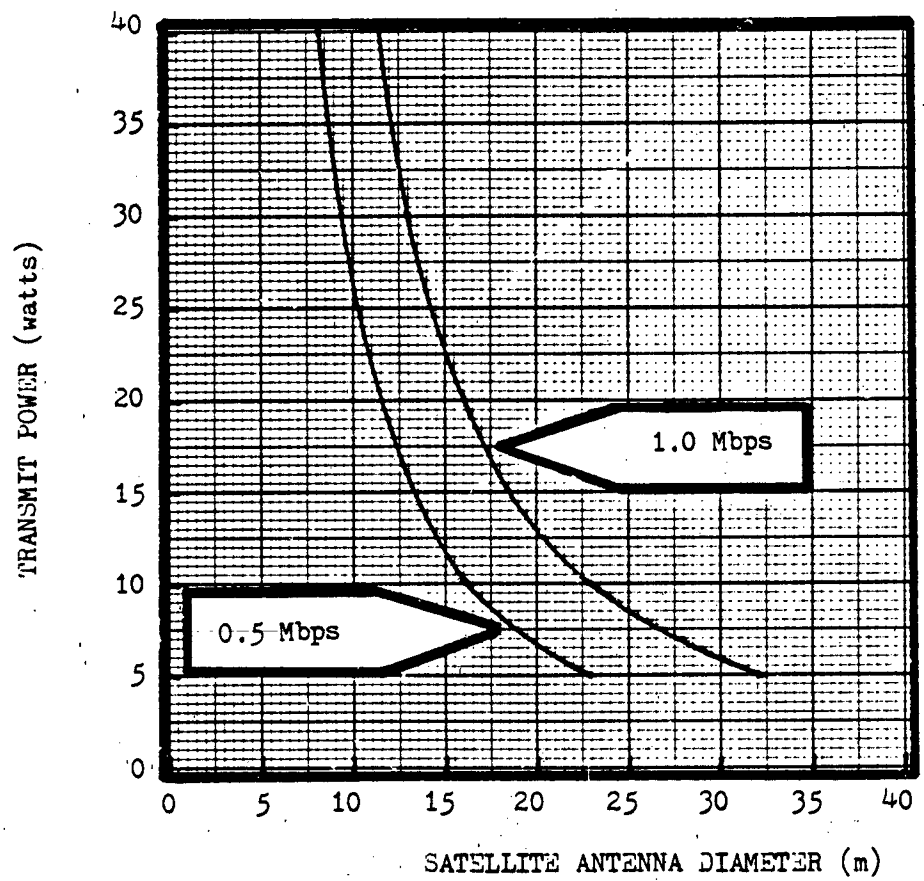


Figure 25: Transmit Power Versus Satellite Antenna Given a 1.0 and 0.5 Mbps Rate and 2.148 dB RV Antenna Gain

Table 5

Transmit Power Effect on Satellite Antenna Diameter

Given a 1.0 Mbps Data Rate and 2.148 db RV Antenna Gain

Transmit Power (watts)	Received Signal (dBw)	Req'd Satellite Antenna Gain (dB)	Req'd Satellite Antenna Diameter (m)
5	-181.4	53.6	32.0
10	-178.4	50.6	22.7
15	-176.7	48.9	18.5
20	-175.4	47.6	16.1
25	-174.4	46.6	14.3
30	-173.6	45.8	13.1
35	-173.0	45.2	12.2
40	-172.4	44.6	11.4

where

g = required gain of the satellite antenna in dB in order to achieve a 1 Mbps data rate.

For example, in Table 5 a received signal level of -181.4 dBw results in a required satellite antenna gain (from Equation (18)) of 53.6 dB for a 1 Mbps data rate.

Next, Equation (2) can be rearranged to yield the antenna diameter required to obtain a certain gain:

$$g = 10 \operatorname{Log}\left[\left(\frac{\pi d}{\lambda}\right)^2 n\right] \tag{2}$$

$$\frac{\lambda}{\pi}\sqrt{10^{g/10} \div 0.4} = d \tag{19}$$

For the case of g = 53.6 dB and λ = 0.133 (f = 2260 MHz), d = 32 meters. In other words, for an RV with a dipole antenna and a 5 watt transmitter, a 1 Mbps data rate can be achieved with a 32 meter diameter satellite antenna.

Note from Figure 25 that an increase in transmit power from 5 to 10 watts for a 1 Mbps rate results in a reduction of 9.3 meters in the required satellite antenna diameter. Adding an additional 5 watts (total of 15) results in an additional antenna reduction of only 4.2 meters, and going from 15 to 20 watts results in a mere 2.4 meter reduction. Thus, there is a definite diminishing return for increasing transmitter power. A reduction in antenna diameter of 9.3 meters by increasing transmitter power to 10 watts should be significant in terms of satellite cost and launch cost.

Table 6

Transmit Power Effect on Antenna Diameter Given a 0.5 Mbps Data Rate and 2.148 dB RV Antenna Gain

Transmit Power (watts)	Received Signal (dBw)	Req'd Satellite Antenna Gain (dB)	Req'd Satellite Antenna Diameter (m)
5	-181.4	50.7	22.9
10	-178.4	47.7	16.2
15	-176.7	46.0	13.3
20	-175.4	44.7	11.5
25	-174.4	43.7	10.2
30	-173.6	42.9	9.3
35	-173.0	42.3	8.7
40	-172.4	41.7	8.1

The actual numbers for the 0.5 Mbps data rate in Figure 25 are listed in Table 6. The values were calculated in a similar fashion to those in Table 5 except that instead of

Equation (18), Equation (20) was used.

$$-130.683 - (\text{received dBw}) = g \tag{20}$$

The slight difference between Equations (18) and (20) is due to the fact that the former was derived with a 1 Mbps data rate, and the latter with a 0.5 Mbps data rate. Note that the 0.5 Mbps curve in Figure 25 is slightly steeper than the one for 1 Mbps. An increase from 5 to 10 watts of transmit power results in only a 6.72 meter satellite antenna reduction (as compared to the 9.3 meter reduction for the 1 Mbps rate). Increasing from 5 to 10 watts results in a 2.97 meter reduction (compared to a 4.2 meter reduction for 1 Mbps).

The primary disadvantage of increasing transmitter power is the increased cost associated with the reentry vehicle. The same arguments against the sophisticated reentry vehicle approach in Chapters V and VI apply here. There are thousands of reentry vehicles on which more money would be spent, and the cost savings would apply to only one satellite.

Recall that doubling the transmitter power has the same affect on the telemetry link as increasing the reentry vehicle gain by 3 dB. If a decision is made to increase the money spent on the reentry vehicle, it would be worthwhile to perform a cost analysis to determine which is the cheapest way to increase the received signal strength. It is suspected that for small increases, improving antenna design would be less expensive than modifying the transmitter. For large gain improvements, however, both antenna and transmitter modifications may be equally prohibatively costly.

Frequency

One method of trying to improve the bit rate of a reentry vehicle to satellite telemetry data link without increasing transmitter power or antenna gain is to increase the transmitting frequency. The primary disadvantage of increasing frequency is that the footprint of the satellite antenna beam on the Earth is reduced. This, in turn, imposes stricter requirements for antenna pointing accuracy. Table 7 shows the effects of increasing frequency on free space loss, satellite antenna gain, and footprint for a 55 meter antenna. Equations (1) thru (4) were used to calculate these values. Frequencies above 10 GHz were not considered because of the increase in rain loss at those frequencies.

Note how rapidly the footprint decreases as frequency is increased. A footprint of 23.8 kilometers implies a satellite antenna beamwidth of only 0.0382 degrees.

The required pointing accuracy of the antenna would be one half that figure, or 0.019 degrees. It should be recalled that the more massive the antenna, the more difficult it is to point the antenna with the same accuracy.

Table 7

Effect of Increasing Frequency

on a 55 Meter Parabolic Antenna

Frequency (GHz)	Free Space Loss (dB)	Antenna Gain (dB)	3dB Beamwidth (degrees)	Footprint (km)
1	-183.50	55.20	0.3818	238.5
2	-189.50	61.20	0.1909	119.2
3	-193.05	64.75	0.1273	79.5
4	-195.56	67.20	0.0955	59.6
5	-197.50	69.19	0.0764	47.7
6	-199.00	70.77	0.0636	39.7
7	-200.40	72.08	0.0547	34.2
8	-201.60	73.27	0.0477	29.8
9	-202.70	74.38	0.0420	26.2
10	-203.50	75.21	0.0382	23.8

Another very important fact that can be inferred from Table 7 is that the increase in satellite antenna gain is exactly cancelled out by the increase in free space loss. If columns two and three of Table 7 are added, the result would be a net reduction of approximately -126.16 dB for each frequency. Thus the amount of improvement in the telemetry link due to increasing frequency can be determined by examining the antenna of the reentry vehicle. For the dipole antenna used in the simple reentry vehicle, the length of the dipole varies with wavelength and its gain is approximately 2.148 dB regardless of frequency. Thus, for the sophisticated satellite approach of Chapter IV, increasing the frequency will not improve the telemetry link. Improvement will be obtained only if the reentry vehicle antenna gain improves with frequency.

For the sophisticated reentry vehicle approach, the 0.14 meter RV antenna's gain will improve with increasing frequency. Table 8 shows the improvement in gain for this antenna and the decrease in the antenna's beamwidth. Note that the pointing accuracy for the reentry vehicle's antenna must increase as the beamwidth decreases. However, even at 10 GHz there is still a large allowable pointing error of 7.5 degrees. The maximum allowable pointing error is one half of the beamwidth (just as the maximum allowable pointing error for the satellite antenna is one half its beamwidth).

Table 8

Effect of Increasing Frequency on a 0.14 Meter Parabolic Antenna

Frequency (GHz)	Antenna Gain (dB)	3dB Beamwidth (degrees)	Maximum Pointing Deviation (degrees)
1	-0.66	150.0	75.00
2	5.36	75.0	37.50
3	8.89	50.0	25.00
4	11.38	37.5	18.75
5	13.32	30.0	15.00
6	14.91	25.0	12.50
7	16.22	21.5	10.75
8	17.41	18.8	9.40
9	18.52	16.5	8.25
10	19.34	15.0	7.50

The values in Table 8 are depicted in Figures 26 and 27. Note that the effect of increasing frequency are not linear. The benefits of increasing frequency by 1 GHz diminish with increasing frequency.

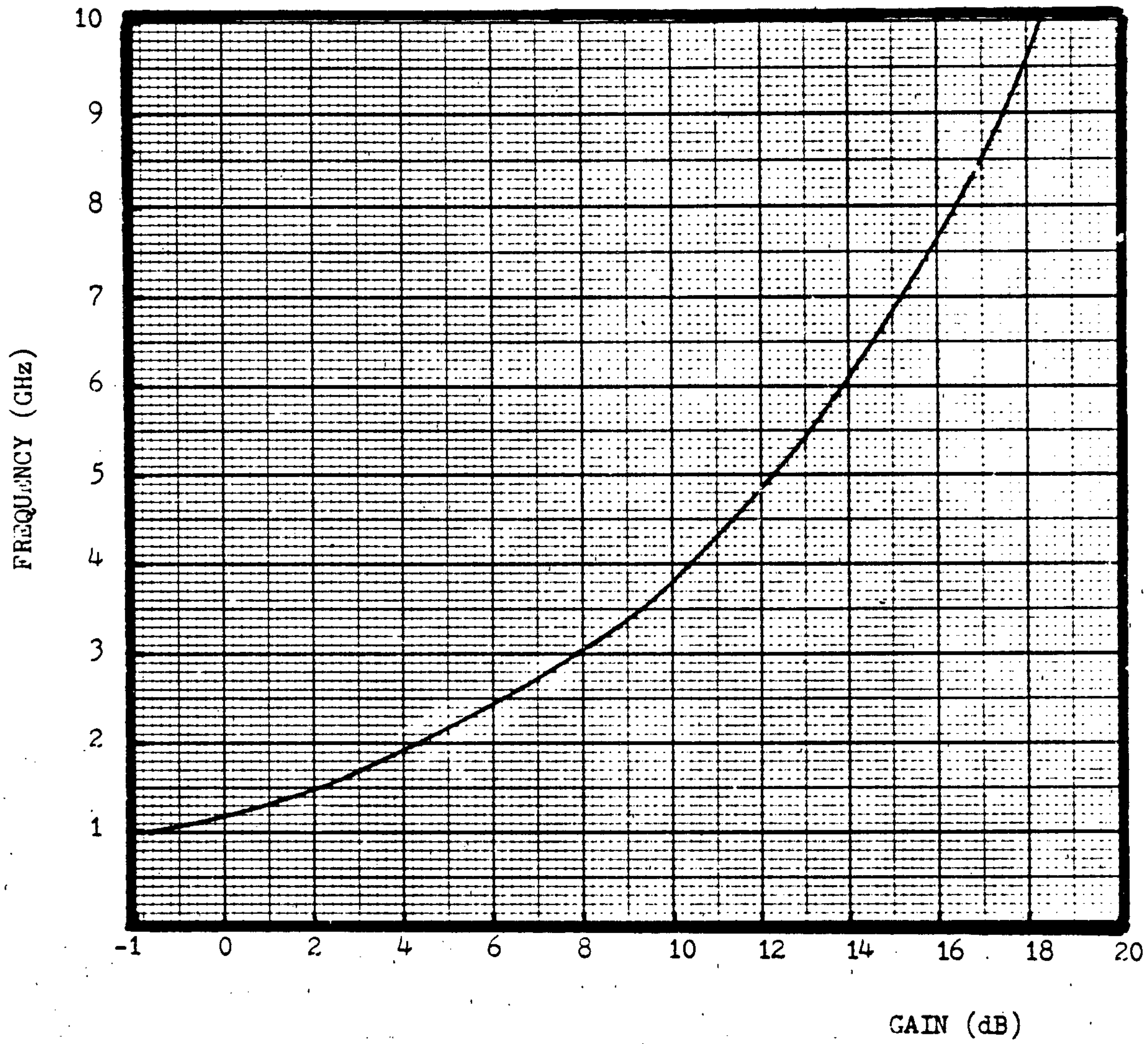


Figure 26. Frequency Versus Gain For a 0.14 Meter RV Antenna

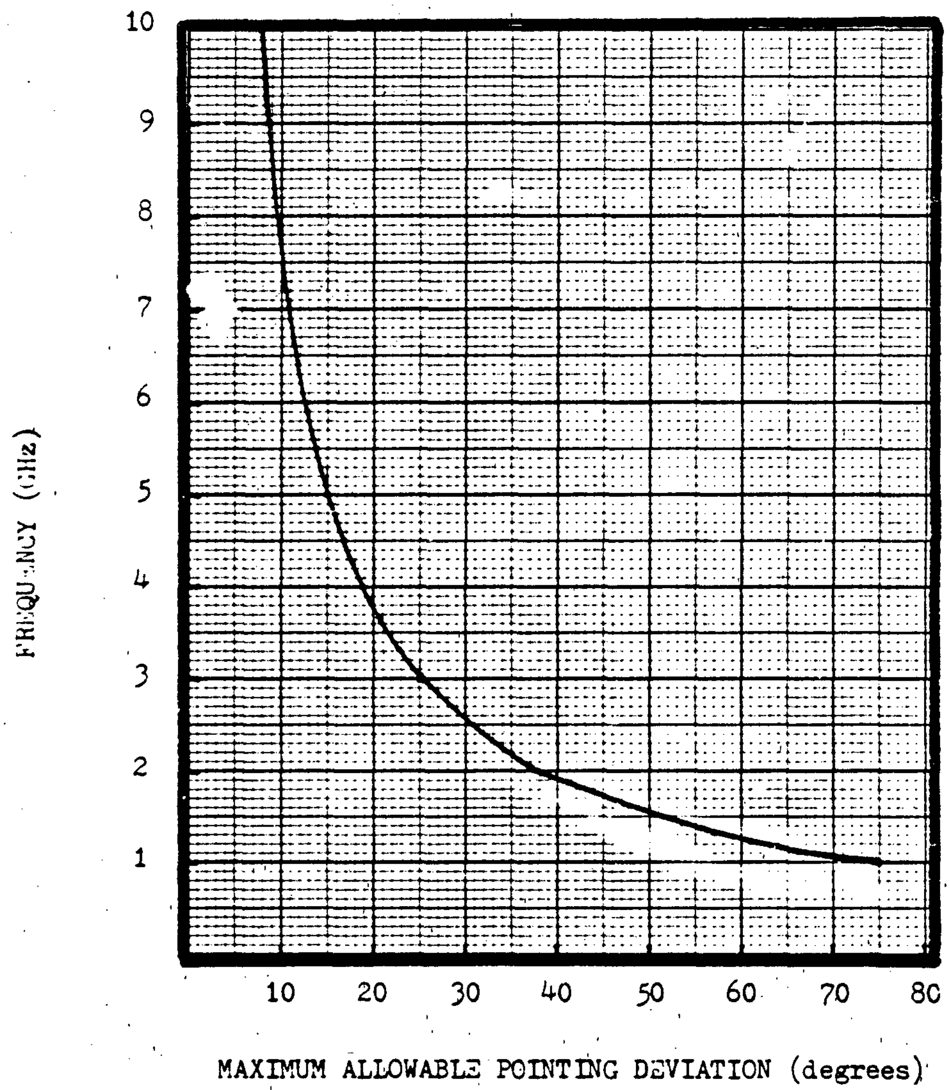


Figure 27. Frequency Versus Maximum Allowable Pointing Deviation for a 0.14 Meter RV Antenna

There is a tradeoff between the benefits and costs of increasing frequency. The cost of transmitter and receiving equipment generally becomes greater as the frequency increases. Another factor to consider is how the increased gain may reduce the required satellite antenna size. Recall that adding 1 dB of reentry vehicle antenna gain will increase the received signal strength by 1 dBw. Also, adding 1 dB of reentry vehicle gain would allow the gain of the satellite antenna to be decreased by 1 dB and still allow the same data rate. Thus, at a frequency of 10 GHz, a 0.14 meter reentry vehicle antenna would allow a 19.34 - 6.4 = 12.94 dB reduction in satellite antenna gain (as compared to the required gain at 2260 MHz, where the RV antenna gain is 6.4 dB). To determine the corresponding reduction in the diameter of the satellite antenna, Equations (13), (18), and (19) must be used.

In Equation (13), the received signal level for a 0.14 meter RV antenna at 2260 MHz was found to be -177.2 dBw. The required satellite antenna gain to achieve a 1 Mbps data rate for this signal strength can be found by using Equation (18):

$$-127.8 - (\text{rec dBw}) = g \tag{18}$$

$$-127.8 - (-177.2) = 49.4 \text{ dB} \tag{21}$$

The required satellite antenna diameter required for a gain of 49.4 dB is found by using Equation (19):

$$\frac{\lambda}{\pi}\sqrt{10^{g/10} \div 0.4} = d \tag{19}$$

$$\frac{0.133}{\pi}\sqrt{10^{49.4/10} \div 0.4} = 19.8 \text{ meters} \tag{22}$$

This is the required diameter at a frequency of 2260 MHz. Increasing the frequency to 10 GHz allows a reduction in satellite antenna gain of 12.94 dB. Thus, the required satellite antenna gain is:

$$49.4 - 12.94 = 36.46 \text{ dB} \tag{23}$$

Using Equation (19) and a wavelength of 0.03 meters (f = 10 GHz), the satellite antenna diameter is:

$$\frac{0.03}{\pi}\sqrt{10^{36.46/10} \div 0.4} = 1.00 \text{ meters} \tag{24}$$

Thus, the net reduction in required diameter is 18.8 meters. A diameter of only 1.00 meter is relatively small for a satellite antenna (recall that the TDRS has a 4.9 meter antenna). A review of the conditions under which a 1.00 meter antenna would suffice is necessary to prevent any misunderstanding.

Equation (18) gives the required satellite antenna gain based on a particular received signal level. This equation (derived from Equation (7)) is based on the sensitiveity of the receiver used aboard the Tracking and Data Relay Satellite. The TDRS receiver operates near frequencies of 2260 MHz (7:4-84). For Equation (18) to be valid for the

1.00 meter antenna case, the receiver used must be just as sensitive at 10 GHz as the TDRS receiver is at 2260 MHz (the effects of varying receiver sensitivity are examined later in this thesis). Note also that the primary reason why increasing frequency from 2 to 10 GHz improves the telemetry link is that the gain of the 0.14 meter reentry vehicle antenna increases from 5.36 to 19.34 dB. For an RV antenna whose gain remains relatively constant with increasing frequency (such as a dipole), there will be virtually no reduction in the required diameter of the satellite antenna.

Antenna Efficiency

The conclusions reached in this thesis are all based on an antenna efficiency of 40 percent (see Appendix B for justification). However, for the readers' planning purposes it may be useful to examine how changes in antenna efficiency affect the telemetry link problem. Changes in antenna efficiency are confined to this section of the thesis alone.

Antenna efficiency is used whenever the parabolic antenna gain equation (Equation (2), given below) is employed.

$$g = 10 \text{ Log}\left[\left(\frac{\pi d}{\lambda}\right)^2 n\right] \qquad (2)$$

Table 9 shows how changing efficiency affects a 32 meter antenna's gain at 2260 MHz. A diameter of 32 meters was chosen as this is the required diameter for a 1 Mbps data

Table 9

Affect of Changing Efficiency on a 32 Meter Parabolic Antenna at 2260 MHz

Efficiency (%)	Gain (dB)	Increase in Gain Due to a 5% Rise in Efficiency (dB)
20	50.58	--
25	51.55	0.97
30	52.34	0.79
35	53.01	0.67
40	53.59	0.58
45	54.10	0.51
50	54.56	0.46
55	54.97	0.41
60	55.35	0.41
65	55.70	0.35
70	56.02	0.32
75	56.32	0.30
80	56.60	0.28

rate given a 5 watt transmitter and a dipole RV antenna (from Table 5).

Perhaps the most useful illustration of the affect of changing efficiency is how it affects required antenna size for a constant gain. Table 10 shows the necessary changes in antenna diameter in order to maintain a constant gain of 53.59 dB at 2260 MHz as efficiency is varied. A satellite antenna gain of 53.59 dB was chosen as this would allow a 1 Mbps data rate to be achieved given a reentry vehicle with a 5 watt transmitter and a dipole antenna.

Table 10

Affect of Changing Efficiency on Parabolic Antenna Diameter for a Constant Gain of 53.59 dB at 2260 MHz

Efficiency (%)	Antenna Diameter (m)	Decrease in Diameter Due to a 5% Rise in Efficiency (m)
20	45.3	--
25	40.5	4.8
30	37.0	3.5
35	34.2	2.8
40	32.0	2.2
45	30.2	1.8
50	28.6	1.6
55	27.3	1.3
60	26.1	1.2
65	25.1	1.0
70	24.2	0.9
75	23.4	0.8
80	22.6	0.8

The required antenna diameter was calculated by modifying Equation (19) as shown below and substituting in different values for antenna efficiency.

$$\frac{\lambda}{\pi}\sqrt{10^{g/10} \div 0.4} = d \qquad (19)$$

$$\frac{0.133}{\pi}\sqrt{105.359} \div \sqrt{E} = d \qquad (25)$$

$$20.24 \div \sqrt{E} = d \qquad (26)$$

where

E = antenna efficiency

d = antenna diameter

λ = wavelength

g = antenna gain (in dB)

The results in Table 10 are graphically represented in Figure 28. Note that the antenna diameter does not decrease linearly with increasing efficiency.

Thus the antenna diameter can vary as much as 22.7 meters over a range of 20 to 80 percent efficiency. Even if the estimate of 40 percent antenna efficienty is accurate to plus or minus 10 percent, this would still allow the antenna diameter to vary by as much as 8.4 meters. This is a significant uncertainty given the fact that the largest satellite communications antenna placed into space to date is approximately 9.1 meters. The reader should consult Appendix B to consider the level of confidence that should be placed in the 40 percent figure.

Receiver Sensitivity

Throughout most of this thesis, most calculations of achievable data rates are based on the sensitivity of the receiver aboard the Tracking and Data Relay Satellite. The TDRS receiver was selected as it was designed specifically for receiving telemetry from a low power source, and because it is representative of the state of the art of hardware that is currently operating in space. The first TDRS was launched in 1983 (20:154).

Since the receiver aboard the proposed telemetry relay satellite may be more or less sensitive than the TDRS

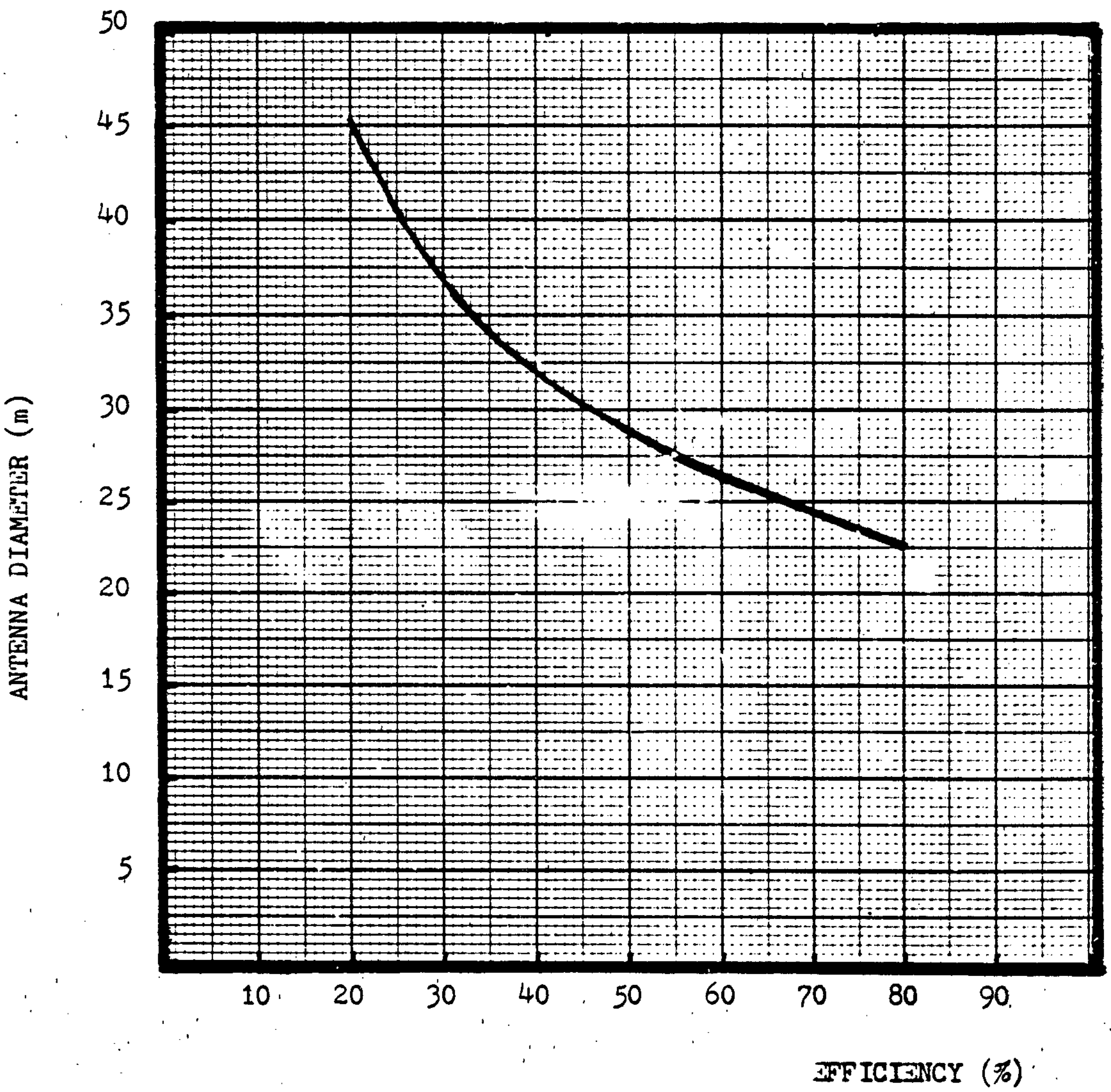


Figure 28. Affect of Changing Efficiency on Parabolic Antenna Diameter for a Constant Gain of 53.59 dB at 2260 MHz

receiver, it is useful to examine the affect of changing receiver sensitivity on the achievable data rate. Using the TDRS receiver as a baseline, a one percent improvement in receiver sensitivity is defined as sufficient improvement to allow a one percent weaker received signal to achieve the same data rate as the unimproved TDRS receiver. Figure 29 shows the affect of increasing and decreasing the receiver's sensitivity (note that the received signal level scale is smaller than in other figures).

The curves in Figure 29 are based on increasing and decreasing the TDRS values by 5 and 10 percent. For example, at a received signal strength of -165 dBw a data rate of 1.024×10^6 bits per second can be achieved with the TDRS. A 5 percent more efficient receiver would allow the same data rate at a 5 percent weaker signal level, or -173.25 dB.

The top of each curve shifts by 8.25 dBw and the bottom of each curve shifts by 9.4 dBw with each 5 percent change in sensitivity. At a received signal level of -188 dBw the TDRS receiver can achieve a data rate of 4,000 bits per second. Improving the receiver by 5 percent would allow a ten fold increase in the data rate, or 40,000 bits per second for the same received signal level. A 10 percent improvement would allow a 300,000 bits per second rate.

From the above information it can be stated that for reentry vehicles with a telemetry bit rate of 1×10^6, a 5 percent improvement in efficiency in the TDRS receiver

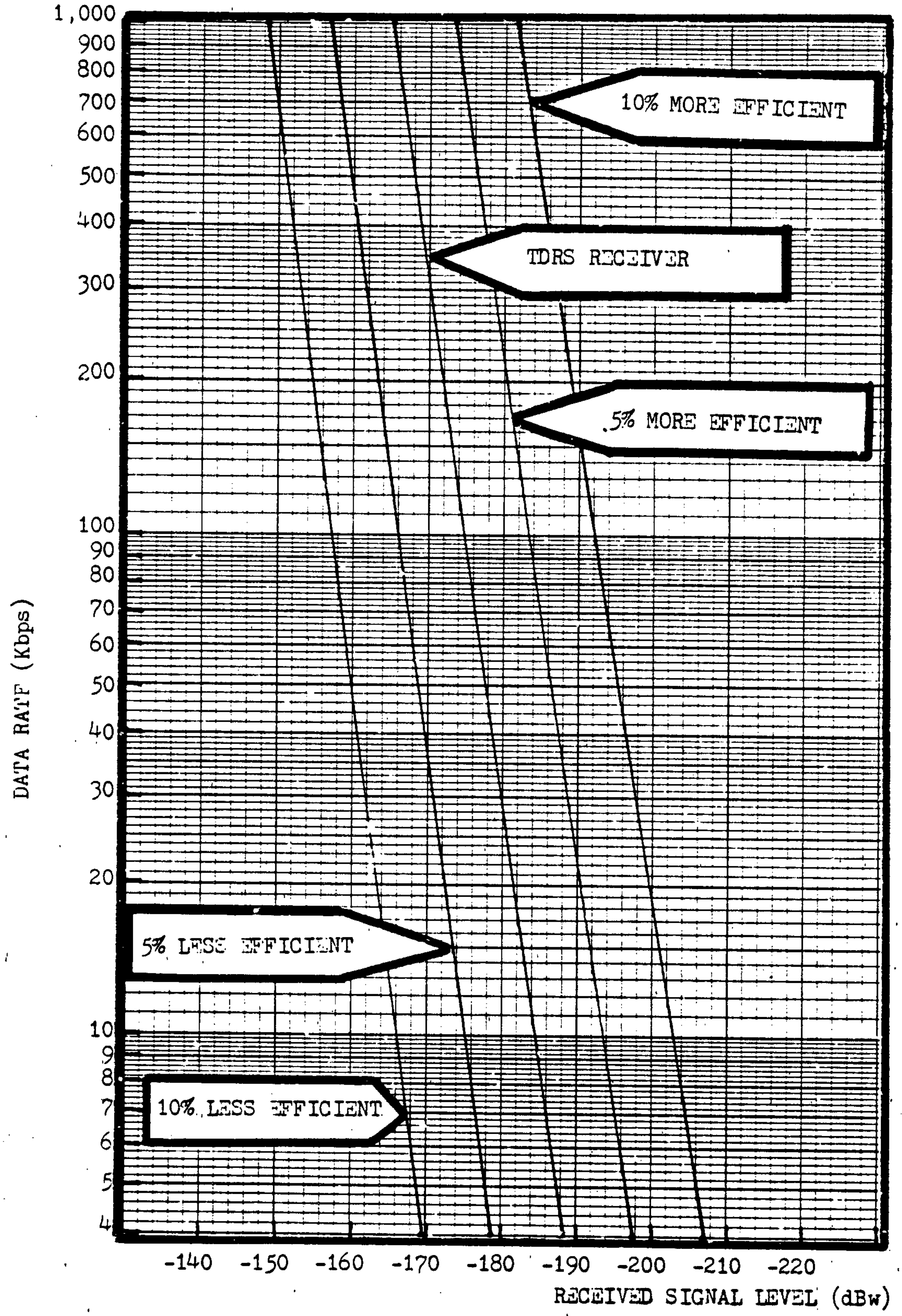


Figure 29. Changing Receiver Sensitivity
(4.9 m antenna)

would allow an 8.25 dBw weaker signal to achieve the same data rate. For a 500,000 bit per second rate, a 5 percent improvement would allow a 3.5 dBw weaker signal to achieve the same data rate. Thus, improving receiver sensitivity is an alternative to increasing satellite antenna gain, reentry vehicle antenna gain, or transmitter power. A 5 percent improvement in receiver sensitivity for a 1×10^6 bit rate would allow the use of a satellite antenna with 8.25 dB less gain. This would significantly reduce the required diameter of the satellite antenna. Referring to Table 1, if a 40 meter satellite antenna is used with the current TDRS receiver, a 5 percent improved sensitivity receiver would require only approximately a 15 meter satellite antenna (which has approximately 8.5 dB less gain than a 40 meter antenna) to achieve the same data rate.

There are many factors involved, however, in improving receiver sensitivity, and a 5 percent improvement may be difficult to obtain. Major changes in the modulation scheme may be required. This would imply changes to the reentry vehicle transmitter as well. Thus, the cost of increasing telemetry link performance due to increased receiver sensitivity may involve receiver and reentry vehicle transmitter modification costs. These costs must be compared to the cost savings of a smaller satellite antenna to determine the most desirable method of increasing telemetry link performance.

VIII. Conclusions and Recommendations

Conclusions

The conclusions in this thesis are based on the following assumptions, stated in order of their perceived importance:

1. It is desirable to keep the satellite antenna diameter to a minimum.

2. It is desirable to keep the sophistication of the reentry vehicle telemetry system down to a minimum.

3. The parabolic antenna efficiency is 40 percent, the RV transmit power is 5 watts at 2260 MHz, and the desired data is between 0.5 and 1 Mbps.

Recommended Option 1. Since keeping the satellite antenna diameter to a minimum has been assumed to have the highest priority, the first recommended option is to use a sophisticated reentry vehicle with a pitch fixed at the reentry angle as shown in Figure 24. The reentry vehicle would have a 14 cm parabolic antenna rigidly mounted on its base. Upon separation from the launching booster, the RV would rotate until the nose of the reentry vehicle was in the proper attitude for reentry and would remain in this position throughout the entire flight. This would mean that no additional antenna pointing would be required, due to the 66 degree beamwidth of the antenna. This thesis does not examine the difficulties (if any) involved in orienting the reentry vehicle in this position, or the problems that may be involved in maintaining antenna structural integrity during reentry. It is suspected, however, that a base mounted antenna would be fairly well protected against the effects of reentry.

From Equation (12), the gain of a 14 cm antenna was found to be 6.4 dB, resulting in a received signal level of -177.2 dBw. For a 1 Mbps data rate, the gain of the satellite antenna would be (from Equation (18)):

$$-127.8 - (\text{received dBw}) = g \tag{18}$$

$$-127.8 - (-177.2) = 49.4 \text{ dB} \tag{27}$$

Thus, from Equation (19) the required diameter of the satellite antenna would be:

$$\frac{\lambda}{\pi}\sqrt{10^{g/10} \div 0.4} = d \tag{19}$$

$$\frac{0.133}{\pi}\sqrt{217{,}741} = d \tag{28}$$

$$19.8 \text{ m} = d \tag{29}$$

While a 19.8 meter diameter antenna is large, it is significantly smaller than the 55 meter antenna mentioned in Chapter III as being developed by the Lockheed Missiles and Space Company.

If the data rate is reduced to 0.5 Mbps, then the required satellite antenna gain is (from Equation (20)):

$$-130.683 - (\text{received dBw}) = g \qquad (20)$$

$$-130.683 - (-177.2) = 46.517 \text{ dB} \qquad (30)$$

Thus, from Equation (19) the required satellite antenna diameter for a data rate of 0.5 Mbps would be:

$$\frac{0.133}{\pi}\sqrt{112{,}109} = d \qquad (31)$$

$$14.2 \text{ m} = d \qquad (32)$$

As expected, the lower the data rate, the smaller the required satellite antenna size. Note that increased diameters may be required if it is determined that a large link margin is necessary. However, a 2.8 dBw margin is already built into the above numbers, as the performance equation (Equation (7)) and performance figures (Figures 5-21)) have a 2.8 dBw margin built into them (see Appendix A for Equation (7) derivation).

Recommended Option 2. Instead of using a parabolic antenna for the reentry vehicle, use a 2.148 dB dipole mounted on the base of the RV. The disadvantage of this approach is that the antenna provides 4.252 dB less gain than the parabolic antenna of Option 1. However, there would no longer be a requirement that the reentry vehicle nose point at the Earth during the entire flight. Also the telemetry signal could still be received by ground stations in the event of satellite failure. Thus, the disadvantage of reduced RV antenna gain is offset by the wider beamwidth.

The required satellite antenna diameters given a 2.148 dB gain RV antenna have previously been calculated, and they are listed in Tables 5 and 6. For a 1 Mbps and a 0.5 Mbps data rate, the required satellite antenna diameters are 32 m and 22.9 m respectively.

Validity of Conclusions. Theoretical calculations do not always accurately model the real world environment. Thus it is useful to examine how valid the data and the conclusions presented in this thesis are. In Chapter I it was stated that only one telemetry link would be considered in this thesis. In practice, several reentry vehicles would be in flight simultaneously, and the satellite would receive telemetry from each RV. The achievable data rate of the satellite receiver may decrease as the number of telemetry signals increases. Thus a higher gain (and therefore larger diameter) satellite antenna may be required. For the TDRSS satellite, the minimum received signal level must be 8.5 dBw higher for multiple access signals than for single access telemetry. This is true for bit rates of either 4,000 bps or 32,000 bps (the TDRSS does not have a high data rate multiple access capability) (7:4-83). This is one area recommended for further study.

Another factor to consider when judging the validity of the conclusions in this thesis is that the free space loss has been calculated to be 190.56 dB (as in Equation (9)). This is based on a satellite to reentry vehicle distance of 35,784 km, the same distance from the surface of the Earth to geosynchronous orbit. The TDRS User's Guide claims a 192.2 dB free space loss based on a 45,510 km distance between the TDRS and the transmitting spacecraft (22:A-2,A-9) (see also Appendix A). This assumes that the transmitting spacecraft is in a 2,000 km orbit around the Earth, and that a worst case geometry exists such that the Earth almost eclipses the line of sight path between the TDRS and the transmitting spacecraft. The 35,784 km distance is probably a more reasonable estimate for most reentry vehicle missions, since their maximum altitude is only 637 km (approximately) (17:24), and the telemetry receiving satellite could be stationed over the halfway point of the RV's trajectory. However, the reader should be aware that the amount of free space loss will vary significantly (and thus the required diameter of the satellite antenna will vary significantly) as the postulated reentry vehicle to satellite distance varies.

Another real world environmental problem that should be considered is the attenuation of the telemetry signal when the RV first reenters the Earth's atmosphere. Telemetry reception may not be a critical requirement during this short phase of the flight. However, the attenuation due to reentry is usually quite severe, and a study of how much additional gain would have to be added to maintain the link may be justified.

There are many other real world considerations which may affect the validity of the data in this thesis. There may be unexpectedly high intentional or unintentional radio frequency interference from unknown sources. Problems in manufacturing may result in a dipole antenna with less than 2.148 dB gain, smaller than expected beamwidth, coupling losses between the RV transmitter and antenna, and less than 5 watts of transmitter power.

Thus it is useful to review how unexpected degradations in the telemetry signal may affect the satellite diameter. In the first recommended option of this chapter the required satellite antenna gain for a 1 Mbps data rate was 49.4 dB, indicating a satellite antenna diameter of 19.8 m. A quick way to determine how much the satellite antenna diameter would have to increase if, for example, the telemetry signal was 5 dBw weaker than expected, is to refer to Table 1. A 5 dBw weaker signal would have to be compensated for by a 5 dB higher gain antenna. From Table 1, a 35 m antenna would provide the required 54.4 dB gain. This is an increase in diameter of 15.2 m. This is a significant increase in size, although the antenna is still of apparently managable diameter.

For the second recommended option of this chapter, the required satellite antenna gain for a 1 Mbps data rate is 53.6 dB, indicating a 32 m antenna diameter. If the actual telemetry signal is 5 dBw less than expected due to the real world problems mentioned earlier, then (from Table 1) the antenna diameter must be increased to approximately 57 m to maintain the same data rate (note that Equations (18) and (19) would provide a more accurate number than estimating from the table).

In summary, planners of a reentry vehicle to satellite telemetry link must keep in mind that small uncertainties in the amount of received power at the satellite will significantly affect the required diameter of the parabolic satellite antenna. To increase the gain of a 40 m antenna by 6 dB, the diameter would almost have to be doubled (reference Table 1). Therefore, in order to keep the diameter of the satellite antenna down, it is desirable to increase the gain of the RV antenna as much as possible. Thus, the first recommended option (0.14 m parabolic RV antenna) is preferred over the second option (dipole RV antenna).

Changing Assumption 3. Only a few general remarks will be made about changing frequency, antenna efficiency, and transmit power. At the beginning of this chapter it was stated that these variables would be assumed constant at their present day levels. While on the surface increasing these three parameters appears to be desirable, (recall from the discussion on Table 7 that increasing frequency will not be an improvement if a dipole antenna is used on the RV) it is not at all certain that present day hardware is capable or cost efficient enough to be used. For example, it is unknown if a 25 watt 10 GHz reentry vehicle transmitter can be inexpensively built to operate under the severe physical and electrical constraints of an RV. Also, the satellite receiver may not be as sensitive at 10 GHz.

The detailed discussion in Chapter VII, however, should give the reader some indication as to whetner or not increasing transmit power, frequency, antenna efficiency and receiver sensitivity is worthy of further investigation.

Leaving aside the question of cost and construction feasibility, a review of Chapter VII will emphasize the potential benefits of each parameter in relation to the other. Compare the following pieces of data:

1. Doubling the transmitter power would allow the gain of either the satellite or RV antenna to be decreased by 3 dB with no degradation in performance. Is the cost of such a transmitter justified by cost saved on the smaller antenna (refer to Table 5 and 6)?

2. Increasing antenna efficiency from 20 to 80 percent for a 32 m diameter parabolic antenna results in increasing its gain from 50.58 to 56.60 dB (refer to Table 9). Looked at another way, increasing antenna efficiency from 20% to 80% would allow a reduction in diameter from 45.3 m to 22.6 m and

still maintain a constant 53.59 dB gain (refer to Table 10).

3. An improved receiver that is 5 percent more sensitive than the currently used Tracking and Data Relay Satellite receiver would allow a 40 meter antenna to be reduced to a diameter of only 15 meters (refer to final page of Chapter VII).

4. Increasing the telemetry frequency from 2.26 to 10 GHz increases the 0.14 m RV antenna gain from 6.4 to 19.34 dB (refer to Table 8). Based on this increase, a 19.8 m satellite antenna could be reduced to a diameter of only 1.0 m and still maintain a 1 Mbps data rate (refer to Equations (22) and (24)).

Perhaps the most significant reduction in satellite antenna diameter can be obtained by increasing the fourth parameter listed above. It may also be the most costly method. However, these are the theoretical possibilities, and a cost versus benefit analysis on the affect of increasing each of these four parameters appears to be a worthwhile endeavour.

Recommendations

There are many areas in which meaningful follow on study can be performed on the reentry vehicle to satellite telemetry link problem. Most of these areas would make good topics for master's degree thesis work. The recommended areas of study are as follows:

1. How large an antenna can be mounted on the rear of the RV and still survive the effects of reentering the Earth's atmosphere? (reference: Chapter V)

2. Research planned hardware for future telemetry systems. Is it possible to use higher frequency, increase transmit power, improve receiver sensitivity and improve antenna efficiency? (reference: Chapter VII)

3. What is the cost versus benefit for improving each parameter mentioned in the previous recommendation? (reference Chapter VII)

4. This thesis has assumed a parabolic dish antenna for RV transmission and satellite reception of the telemetry. However, there are other types of antennas such as a spherical reflector or steerable beam phased array, which could be studied. The phased array antenna may prove to be physically smaller and provide more gain when tracking multiple reentry vehicles. It would also eliminate the need for an antenna steering motor.

5. Survey the real world radio frequency interference environment to determine just how much link margin would be required for this telemetry system. (reference Chapter VIII)

6. What is the cost effectiveness of the proposed reentry vehicle to satellite telemetry system as compared to the cost of the currently used ground stations? Is the increased coverage that a satellite would provide worth the increase (if any) in cost? (Some assumptions regarding the

satellite antenna size and the cost of reentry vehicle modification would have to be made). (reference Chapter I)

7. Determine the optimum cost effective combination of reentry vehicle and satellite antenna combination. Recall from Chapter IV that a 65 m diameter satellite antenna may provide sufficient gain to acheve an acceptable telemetry data rate with a currently unmodified reentry vehicle. However, to say that a 65 m space antenna is large is an understatement. Thus the cost of modifying many reentry vehicles may be justified if the cost spread over the life of the satellite is less than the money saved by using a smaller satellite antenna. It is suggested that the analysis be broken into two parts. The first part would determine if a minimal RV modification, such as a dipole would be cost effective. The second part would examine the additional benefit obtained by the more extensive modification of using a parabolic RV antenna and constant reentry vehicle pitch. (reference Chapter IV for RV dipole, and Chapter V for extensive RV modification)

8. Research the problem of multiple RV telemetry links. How is the number of received signals related to the data rate each signal can achieve? (reference Chapter VIII)

Appendix A

The TDRS Receiver

The fundamental basis for the conclusions drawn in this thesis is the sensitivity of the receiver aboard the Tracking and Data Relay Satellite. Equations (6) and (7) (repeated below) are based on the capabilities of the TDRS receiver.

$$\text{Log (bit rate)} = 0.1047 \times \text{ received dBw} + 23.2868 \quad (6)$$

$$\text{Log (bit rate)} = 0.1047 \times (\text{received dBw} + \Delta) + 23.2868 \quad (7)$$

where

Δ = New antenna gain - TDRS antenna gain.

This section of the appendix will describe the data the author relied upon, and the above equations are derived in detail.

One of the services that the TDRS provides is an S-band single access (SSA) data link from a low Earth orbit satellite to the TDRS. According to the user's guide for the TDRS, the achievable data rate is given by (22:3-21)

$$10 \text{ Log (bit rate)} = 34.7 + \text{EIRP} \quad (\text{A-1})$$

or

$$10 \text{ Log (bit rate)} = 35.7 + \text{EIRP} \quad (\text{A-2})$$

depending on which channel is used. The effective isotropic radiated power is that of the low orbit satellite, which in the case of this thesis is that of the reentry vehicle. The EIRP is in units of dBw.

Equations (A-1) and (A-2) assume a 1 x 10-5 bit error rate, a 2255.5 MHz transmit frequency, and a -192.2 dB free space loss (the latter figure is based on a TDRS to low orbit satellite distance of 42,510 km (22:A-2), which is slightly greater than the 35,784 km distance from the surface of the Earth to the TDRS). However, no other losses are taken into account. Thus Equations (A-1) and (A-2) must be modified before being used to approximate realistic operating conditions. Losses are taken into account by subtracting their value in dBw from the right hand side of Equations (A-1) and (A-2). Figure A-1, taken from the TDRS User's Guide, depicts three different curves. The curve marked with the letter A corresponds to the equation:

$$10 \text{ Log (bit rate)} = 32.2 + \text{EIRP} \qquad \text{(A-3)}$$

The curve indicated by the letter B corresponds to:

$$10 \text{ Log (bit rate)} = 31.2 + \text{EIRP} \qquad \text{(A-4)}$$

The curve indicated by the letter C corresponds to:

$$10 \text{ Log (bit rate)} = 30.7 + \text{EIRP} \qquad \text{(A-5)}$$

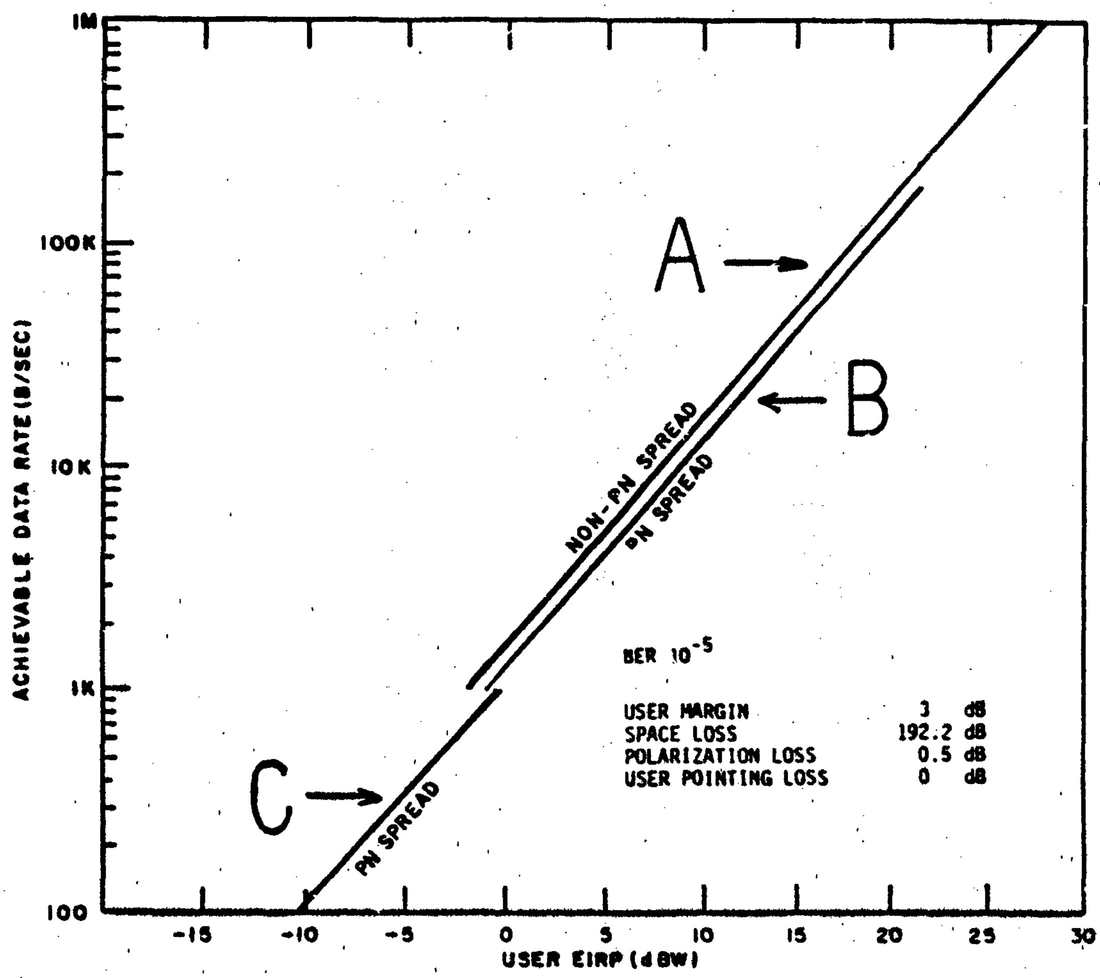


Figure A-1. Example TDRS SSA Performance
Source (22:A-9)

Equations (A-3), (A-4), and (A-5) are only examples of mathematical relationships that could describe a communications link between a satellite and a reentry vehicle. Equation (A-3) takes into account a 3 dB user margin and a 0.5 dB polarization loss. Subtracting 3.5 dB from Equation (A-2) yields Equation (A-3). Thus, a reasonable assumption as to the amount of loss in the communications link is required. It is useful to note that if the system has to be pushed to the limit of its capability, the TDRS receiver is capable of maintaining lock on the signal despite a 3 dB EIRP fade relative to the EIRP necessary for a certain data rate (22:3-32). Thus a 3 dB user margin may not be necessary in establishing a data link.

One type of loss that the TDRS User's Guide pays particular attention to is loss due to radio frequency interference (RFI). An average of approximately 2 dBw is subtracted from the transmitted signal strength because of RFI. The effect of RFI increases with increasing antenna pointing error (22:K-4).

Another method of describing the performance of the TDRS receiver is in terms of the power received at the TDRS antenna (recall that received power is equal to the EIRP of the reentry vehicle minus free space loss and all other losses). In the radio interface control document for the TDRS the ideal required received power for a data rate of 1.024 Mbps (at a 1 x 10-5 bit error rate) is -167.8 dBw.

Taking into account polarization loss and the presence of RFI, a received power level of -165 dBw would be required (7:4-84). Data rates of 4,000 bps and 32,000 bps can be obtained with received powers of -188 dBw and -179 dBw respectively, taking into account polarization loss and RFI (approximately 2.8 dBw) (7:4-83).

The above data was used to derive Equations (6) and (7). The major difference between Equations (A-1) through (A-5) and Equations (6) and (7) is that Equations (A-1) through (A-5) use transmitted power, while Equations (6) and (7) use received power. Thus, Equations (A-1) through (A-5) have a greater amount of uncertainty in them because the estimates of various losses in the system must be subtracted from the right hand side of the equations. For example, as stated above, a received signal level of -165 dBw will result in a 1.024 Mbps data rate. Using Equation (A-2) we see that:

$$10 \text{ Log } (1.024 \times 10^6) = 60.103 = 35.7 + \text{EIRP} \qquad \text{(A-6)}$$

Thus, the EIRP must be 24.403 dBw in the ideal case. However, due to various real world losses the actual EIRP must be higher. If the EIRP is 24.403 dBw, and the free space loss from the reentry vehicle to the satellite is -192.2 dB, then the maximum received power at the satellite would be -167.79 dBw. This is in close agreement with the -167.8 dBw figure given earlier as the ideal received power for a 1.024 Mbps data rate. In this example, the received signal level is -165 dBw (due to assumption of non-ideal case). Thus 2.79 dBw must be subtracted from the right hand side of Equation (A-2) for this example. The exact amount that should be subtracted from the right hand side of Equation (A-2) varies as the environmental conditions vary.

There is no clear advantage of using Equation (A-2) over Equation (6), as at some time during calculations for the data link an estimate of the losses in the system must be made. Equation (6) was used in this thesis since the required received power for a certain data rate may give the reader a more intuitive feeling for the sensitivity of the TDRS receiver than the EIRP of the reentry vehicle used in Equations (A-1) and (A-2).

Equation (6) was derived using the data that received signal levels of -165 dBw and -188 dBw produced bit rates of 1.024 Mbps and 4,000 bps respectively. Also used was the knowledge (from Figure A-1) that the log of the data rate increased linearly with increased transmit (or received) power. Thus, using the mathematical relationship governing a straight line:

$$y = mx + b \qquad \text{(A-7)}$$

where

m = slope of the line

b = y intercept point

and inserting the proper values, yields:

$$\text{Log } (1.024 \times 10^6) = m(-165) + b \tag{A-8}$$

$$\text{Log } (4{,}000) = m(-188) + b \tag{A-9}$$

with Equations (A-8) and (A-9) it is possible to solve for m and b.

$$6.0103 = m(-165) + b \tag{A-10}$$

$$3.60206 = m(-188) + b \tag{A-11}$$

Solving Equation (A-11) for b yields:

$$3.60206 + m(-188) = b \tag{A-12}$$

Inserting Equation (A-12) into (A-10) yields:

$$6.0103 = m(-165) + 3.60206 + m(188) \tag{A-13}$$

$$m = 0.104706 \tag{A-14}$$

which implies:

$$b = 23.286788 \tag{A-15}$$

Thus, inserting the values of m and b (rounded off to four places after the decimal) into Equation (A-7) yields Equation (6):

$$\text{Log (bit rate)} = 0.1047 \text{ (received dBw)} + 23.2868 \tag{6}$$

Equation (7), repeated below, was derived so that the affect of using a higher gain antenna with the TDRS receiver could be determined.

$$\text{Log (bit rate)} = 0.1047 \times (\text{recieved dBw} + \Delta) + 23.2868 \quad (7)$$

where

$$\Delta = \text{New antenna gain} - \text{TDRS antenna gain}$$

Equation (7) is derived from Equation (6) and the fact that increasing antenna gain by 1 dB has the exact same affect as increasing the received signal strength by 1 dBw.

A few remarks regarding antenna noise temperature are appropriate at this point. The noise temperature of the satellite receiving antenna depends on the objects within the antenna's field of view (4:171-172). Since the antenna will always be pointed at the Earth, and the Earth will fill the field of view of any 5 to 85 meter antenna (refer to Table 1), the noise temperature of the antenna will be approximately 290 degrees K (24:442). As the diameter of the antenna increases, its gain increases and its footprint on the surface of the Earth decreases. Since "the gain or effective area of the antenna does not influence the noise power delivered by the antenna" (23:302), there should be very little difference in the antenna noise temperature of a 5 meter and an 85 meter antenna if both antennas are pointing at the Earth. Thus, no consideration has been given to small changes in antenna noise temperature due to the difference in the field of view of the different size satellite antennas examined in this thesis. The Earth has been assumed to be a relatively uniform noise source. This enables direct comparison of different antenna performances.

The following is a brief excerpt from the TDRS radio frequency interface control document. It describes the modulation process used in a typical S-band single access data link:

> "4.2.4.2 DG2 High Data Rate Return Link. (User SC)-to-TDRS SSA high data rate return link service will be available on a scheduled basis during intervals that the (user SC)-TDRSS line-of-sight exists. Figure 4-3 (thesis Figure A-2) shows the functional configuration of the (user SC)-to-TDRSS high data rate return link. The link is used to transmit one of three data signals at 1.024 Mb/sec. The data signal is selected from either real-time science data, playback science data, or playback engineering data.
>
> a. The 956-kb/sec real-time science data or playback data is channel encoded using both an outer block code and an inner convolutional code. The outer block code is produced by a Reed-Solomon (RS) encoder with RS symbol interleaving. The outer code is used to correct the channel burst errors occurring at the output of the Rate 1/3 Viterbi decoder.
>
> b. After RS encoding, the 1.024-Mb/sec data is PN scrambled to reduce the magnitude of the spectral lines resulting from repetitive (periodic) data. After PN scrambling, the data is converted to an NRZ-S format. At this point, the 1.024-Mb/sec real-time science data is recorded. When playback science data is to be transmitted on the link, the 1.024-Mb/sec playback science data is selected at this point. The recorded science data is played back in reverse order.
>
> c. The NRZ-S data signal is Rate 1/3 convolutionally encoded to 3.072 megasymbols/sec and Periodic Convolutionally

Interleaved (PCI). The PCI time reorders the contiguous symbols out of the convolutional encoder in such a way that error bursts on the link from pulsed radio frequency interference are randomized by the Periodic Convolutional Deinterleaving (PCD) in the TDRSS ground terminal prior to Rate 1/3 Viterbi decoding.

d. The output of the PCI BPSK modulates the transmit carrier which is derived from a local oscillator. The BPSK modulated return link signal is power amplified, then transmitted at 2255.5 MHz to the TDRS through the LHC-polarized HGA. In the TDRS, the signal is coherently upconverted and transmitted to the TDRSS ground terminal".

where

NRZ-S = Non-return to zero space

DG2 = Data Group 2 (High Data Rate)

SC = Spacecraft

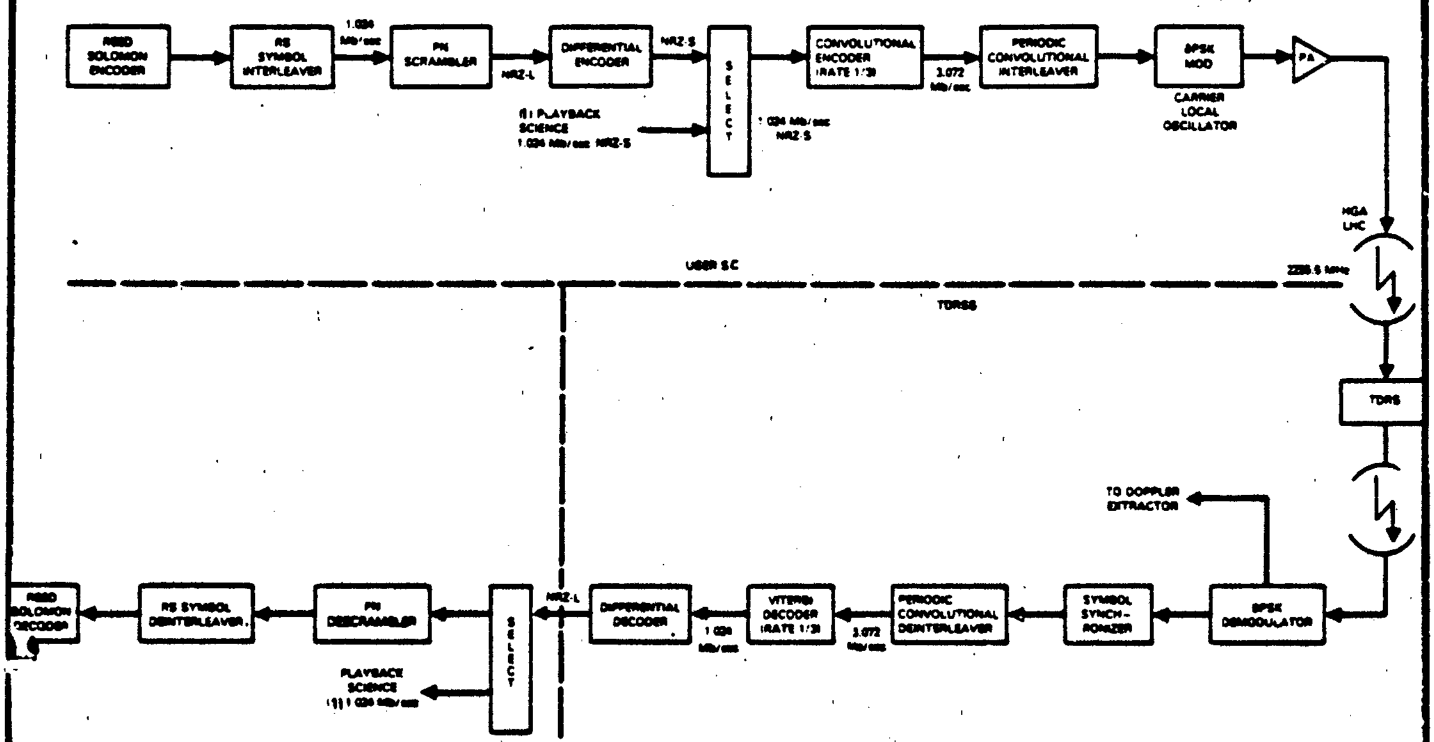
PN = Pseudonoise

HGA = High Gain Antenna (4.9 meter)

LHC = Left Hand Circular

BPSK = Binary Phase Shift Key

SSA = S-band Single Access



Note

1. Data is played back in reverse order.

Figure A-2. User Spacecraft to TDRSS S-band Single Access Return Link (high data rate) Source (7:4-12)

Appendix B

Antenna Efficiency Factor

The antenna efficiency factor used in this thesis to evaluate the gain of a parabolic antenna is 40 percent. The most compelling argument for this percentage is the fact that the 4.9 m TDRS antenna, one of the largest antennas deployed in space to date, has an efficiency of approximately 40 percent. Using the gain equation for a parabolic dish, and the knowledge that the 4.9 m TDRS antenna has a gain of more than 37 dB at 2260 MHz (15:422) we see that:

$$g = 10 \text{ Log}\left[\left(\frac{\pi d}{\lambda}\right)^2 n\right] \tag{2}$$

$$37 \text{ plus} = 10 \text{ Log}\left[\left(\frac{\pi 4.9}{0.133}\right)^2 n\right] \tag{B-1}$$

If the efficiency factor in Equation (B-1) is 40 percent, the gain is 37.3 dB. The gain is 37.07 dB for a 38 percent efficiency factor and 38.9 dB for a 42 percent efficiency factor. Thus a 40 percent efficiency factor appears to be a reasonable choice for use in this thesis.

Further justification is contained in Table B-1. The table lists the characteristics of 19 parabolic antennas currently in use. The data was taken from an instrumentation handbook for the U.S. Air Force Eastern Test Range (3). The first column of the table lists the page number of the handbook from which the data is taken from.

Table B-1

Data to Substantiate Antenna Efficiency Factor

Page	Frequency (GHz)	Diameter (ft)	Gain (dB)	Actual Beamwidth (degrees)	Calculated Beamwidth (degrees)	Efficiency (percent)
2-6	5.70	20	47.5	0.60	0.60	42.5
2-9	5.70	29	53.0	0.38	0.42	71.7
2-11	5.70	28	48.0	0.46	0.43	24.3
2-13	5.70	12	44.0	1.20	1.01	52.7
2-15	5.70	29	51.0	0.38	0.42	45.2
2-19	5.70	16	46.0	--	0.76	47.0
2-22	5.70	30	53.0	0.40	0.40	67.0
2-23	1.28	40	41.0	1.20	1.35	47.1
2-24	0.435	40	31.5	3.50	3.96	45.8
2-29	2.25	80	51.0	0.34	0.38	33.1
2-29	2.25	33	43.0	0.90	0.93	35.5
2-29	2.25	24	41.0	1.35	1.28	42.4
2-30	2.25	30	42.5	1.00	1.02	38.3
2-30	2.25	33	42.2	0.90	0.93	29.6
2-31	2.25	85	48.0	0.40	0.36	16.9
2-32	2.25	33	39.0	0.90	0.93	14.1
2-33	2.25	3	20.5	11.0	10.20	24.2
2-34	2.25	6	28.5	5.00	5.10	38.1
2-34	4.00	6	33.5	2.50	2.87	38.2

The last two columns in Table B-1 list calculated values. The beamwidth of the parabolic antennas were calculated using Equation (3):

$$3 \text{ dB BW} = 70\lambda/d \tag{3}$$

Note how closely the actual beamwidth corresponds to the calculated beamwidth. The average difference between the calculated and actual beamwidth values is only 6.86 percent.

The largest difference between calculated and actual was 15.8 percent (for the 12 ft antenna). In two cases the calculated and actual beamwidths were exactly the same. This should give the reader a fairly high degree of confidence in the ability of Equation (3) to accurately predict the beamwidth of a parabolic antenna.

The last column in Table B-1 was calculated using Equation (2) and solving for the antenna efficiency factor.

$$g = 10 \text{ Log}\left[\left(\frac{\pi d}{\lambda}\right)^2 n\right] \qquad (2)$$

Note that the antenna diameters in Table B-1 are given in feet and therefore the wavelength must also be computed in feet. The average calculated antenna efficiency in the table is 39.9 percent. This gives further support to the assumption of 40 percent antenna efficiency used in this thesis.

The antenna efficiency factor takes into account all of the imperfections which reduce the gain of antenna (such as surface roughness and other items which reduce the receiving aperture) (16:66). Improvement in the sidelobe performance of an antenna may result in decreased efficiency (16:66).

Appendix C

Verification of dB and dBw Addition

Many calculations in this thesis require addition of quantities in units of dB and dBw. Thus it is useful to briefly review why units of dB and dBw can be added while units of dB and dBm cannot be added. Units of dB, dBw, and dBm are calculated using the following mathematical operations:

$$10 \text{ Log } (x) = y \text{ dB} \tag{C-1}$$

$$10 \text{ Log } \frac{x}{1 \text{ watt}} = y \text{ dBw} \tag{C-2}$$

$$10 \text{ Log } \frac{x}{1 \times 10^{-3} \text{ watts}} = y \text{ dBm} \tag{C-3}$$

Note that Equations (C-1) and (C-2) will yield the same value of y for a specific value of x, while Equation (C-3) produces a different result. Thus it is more useful to represent transmitted and received power in units of dBw than dBm since the power can be directly added to antenna gain and free space loss (Equation (C-1)) to determine quantities such as received signal strength (Equation (5)).

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This thesis is intended to be a tool for planners of a reentry vehicle to satellite telemetry link. However, it may be a useful resource to anyone interested in satellite communications, especially those who wish to examine the S-band capability of the Tracking and Data Relay Satellite (TDRS). The thesis should be a stand alone reference for a general overview of the problems concerned. Most of the major problems involved in establishing a telemetry link have been set forth in this one source. The reader is briefed on each problem in sufficient detail to gain some insight as to how the problems affect the quality of the link, how the problems are are related to each other, and some of the tradeoffs that can be performed. A broad range of antenna and transmitter combinations are examined, and their performances are compared.

Specifically, this thesis examines free space loss, rain loss, gain and 3 dB beamwidth of parabolic, slot, and dipole antennas, parabolic antenna footprint on the Earth, the concept of recieved signal strength, reentry vehicle and satellite characteristics, increasing transmit power, varying frequency from 1 to 10 GHz, increasing antenna efficiency, and increasing receiver sensitivity. Key words include: [illegible]

Some preliminary conclusions are drawn, and areas for further study are recommended.

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